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Valorising Organic Waste using the Black Soldier Fly (*Hermetia illucens*), in Ghana

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Abstract

Ghana as a rapidly growing and urbanizing middle-income country is facing a number of challenges, including (1) implementing a sanitary, environmental-friendly, and economically-sound waste management system; (2) increasing its agricultural productivity in a sustainable way to meet the growing domestic food demand; and (3) providing livelihood opportunities in both rural and urban areas. Using the black soldier fly (BSF), a particularly beneficial insect, to locally and cost-effectively valorise abundant, high-impacting, and nutrient rich organic waste streams, such as food waste (FW) and faecal sludge (FS), into affordable and sustainable farming inputs like organic fertilizer and animal feed products, could tackle all these challenges at the same time. Therefore, this study aimed at (1) providing a comprehensive overview of BSF technology; (2) investigating the technical feasibility of valorising food waste and faecal sludge using a low-tech BSF bioconversion system; and (3) assessing the economic viability of such system in the Ghanaian context. First, through an extensive literature review and field visits of BSF units, the different dimensions of the BSF technology were discussed, BSF waste treatment method was compared to other options for organic waste valorisation, case studies of implementation were documented, the status of the research was highlighted, and research gaps were identified. In a second step, a 10-week field work consisting of establishing a BSF colony and recording rearing performance in the one hand, and running two waste treatment trials using a low-tech BSF system on the other hand, enabled demonstrating the technical feasibility of co-digesting FW and FS with the BSF, as well as artificially rearing the BSF in Ghana using a low-tech system. However, further research is needed to characterize the bioconversion products, determine the optimal FW/FS ratio, and optimize the rearing performance of the system. Finally, a cost-benefit analysis was conducted to compare three scenarios: (1) co-composting FW and FS into fertilizer; (2) co-digesting FW and FS with BSF into only animal feed; and (3) co-digesting FW and FS with BSF into both animal feed and fertilizer. By building financial models for each scenario and performing a sensitivity analysis, it was established that, in the Ghanaian context, scenario (3) was the most likely to be viable, as well as the most profitable, followed by scenario (1). On the other hand, scenario (2) was associated with a much lower likelihood to be viable. Eventually, the choice of the optimal valorisation option for FW and FS should consider the local context and priorities.

Key words

Review, case studies, food waste, faecal sludge, co-digestion, low-tech system, cost-benefit analysis (CBA)

Sammanfattning

Ghana, ett snabbväxande medelinkomstland med kraftig urbanisering, står inför ett antal utmaningar, bland annat att (1) införa ett sanitärt, miljövänligt och ekonomiskt avfallshanteringssystem; (2) öka sin jordbruksproduktivitet för att möta den växande inhemska efterfrågan på livsmedel på ett hållbart sätt, och (3) erbjuda möjligheter till försörjning både på landsbygden och i städerna. Genom att använda den svarta soldatflugan (SSF), en särskilt fördelaktig insekt, för att lokalt omvandla rikligt förekommande och näringsrika organiska avfallsströmmar, såsom matavfall (MA) och fekalslam (FS) till prisvärda och hållbara jordbruksinsatsvaror, såsom organiskt gödselmedel och djurfoder, skulle man på ett kostnadseffektivt sätt kunna ta itu med alla dessa utmaningar samtidigt. Därför syftade denna studie till (1) att ge en övergripande översikt över SSF-teknik; (2) undersöka den tekniska möjligheten att skapa värdefulla produkter av matavfall och fekalslam med hjälp av ett biotekniskt system med lågteknologisk SSF i Ghana; och (3) bedöma det ekonomiska systemets bärkraft. Först, baserat på en omfattande litteraturstudie och fältbesök, diskuterades SSF-teknikens olika dimensioner, jämfördes SSF-avfallshanteringsmetoden med andra alternativ för organiska avfallsvalorisationer, dokumenterades fallstudier, redovisades forskningsläget och identifierades kunskapsluckor. I ett andra steg genomfördes ett 10 veckors fältarbete som bestod dels av att etablera en SSF-koloni och dokumentera uppfödningens prestanda, dels att göra två avfallsbehandlingsförsök med hjälp av ett SSF-system med lågteknologi. Därigenom visades att det är tekniskt möjligt att sambehandla MA och FS med SSF, liksom att föda upp SSF i Ghana med hjälp av ett lågteknologiskt system. Det behövs dock ytterligare forskning för att karakterisera slutprodukterna, bestämma det optimala MA/FS-förhållandet och optimera systemets uppfödningens prestanda. Slutligen genomfördes en kostnadsnyttoanalys för att jämföra tre scenarier: (1) kompostering av MA och FS till gödselmedel; (2) sambehandling av MA och FS med SSF till endast djurfoder; och (3) sambehandling av MA och FS med SSF till både djurfoder och gödningsmedel. Genom att bygga modeller för varje scenario och genomföra en känslighetsanalys fastställdes att för Ghana var scenario (3) mest sannolikt livskraftigt, liksom det mest lönsamma, följt av scenario (1). Scenario (2) förknippat med en mycket lägre sannolikhet att vara genomförbart. Till sist bör valet av det optimala behandlingsalternativet för MA och FS ta hänsyn till lokala förhållanden.

Nyckelord

Granskning, fallstudier, livsmedelsavfall, fekalslam, sambehandling, lågteknologiskt system, kostnadsnyttoanalys

Résumé

Le Ghana, pays en voie de développement connaissant une forte croissance et urbanisation, est confronté à un certain nombre de défis, parmi lesquels (1) la mise en place d'un système de gestion des déchets performant du point de vue sanitaire, environnemental, et économique ; (2) l'augmentation durable de sa productivité agricole afin de répondre à la demande alimentaire croissante dans le pays ; et (3) la création d'opportunités économiques pour ses populations rurales et urbaines. Utiliser la mouche soldat noire (MSN), un insecte particulièrement bénéfique, pour valoriser localement et à moindre coût des déchets organiques abondants, riches en nutriments, et responsables d'importants dommages sanitaires et environnementaux, tels que les déchets alimentaires (DA) et boues de vidange (BV), en intrants agricoles écologiques et bon marché, comme des produits alimentaires pour animaux ou de l'engrais organique, contribuerait à relever tous ces défis à la fois. Ainsi, cette étude visait à (1) réaliser un état de l'art de la technologie liée à la MSN ; (2) étudier la faisabilité technique de valoriser les DA et BV à l'aide d'un système à faible technologie reposant sur la MSN ; (3) analyser la viabilité économique d'un tel système dans le contexte Ghanéen. Dans un premier temps, un examen approfondi de la littérature scientifique et des visites d'unités de recyclage utilisant la MSN ont permis d'analyser les différentes dimensions de cette technologie, de la comparer à d'autres options de valorisation pour les déchets organiques, de présenter des études de cas, de donner un aperçu de l'état actuel de la recherche, ainsi que de d'identifier les principales lacunes et besoins en matière de recherche. Dans un second temps, dans le cadre d'une étude de terrain réalisée sur une période de dix semaines, un système d'élevage en captivité de MSN a été mis en place et son efficacité analysée, tandis qu'en parallèle deux séries d'expériences de traitement des déchets ont été réalisées. Ces différentes activités ont permis de démontrer que le co-traitement des DA et BV, ainsi que l'élevage en captivité de la MSN à l'aide d'un système low-tech est techniquement réalisable dans le contexte Ghanéen. Toutefois, des recherches supplémentaires sont nécessaires afin d'analyser les propriétés des produits de valorisation, d'établir le ratio DA/BV optimal, et d'optimiser les performances d'élevage. Enfin, une analyse coûts-bénéfices a été réalisée afin de comparer trois scénarios : (1) co-compostage des DA et BV afin de produire de l'engrais ; (2) co-traitement des DA et BV à l'aide de la MSN débouchant sur la production d'aliments pour animaux ; et (3) co-traitement des DA et BV à l'aide de la MSN pour produire à la fois des aliments pour animaux et de l'engrais. La construction de modèles financiers et la réalisation d'une analyse de sensibilité ont permis de démontrer que dans le contexte Ghanéen, le scénario (3) présentait la plus grande probabilité d'être viable et était le plus rentable, suivi par le scénario (1). En revanche, la probabilité que le scénario (2) soit viable s'est révélée beaucoup plus faible. Ultiment, la sélection de la meilleure méthode de valorisation devrait tenir compte du contexte et des priorités locaux.

Mots clés

Etat de l'art, études de cas, déchets alimentaires, boues de vidange, co-traitement, système low-tech, analyse coûts-bénéfices.

Preface

This report was written as part of a Master degree project in Environmental Engineering and Sustainable Infrastructure at KTH Royal Institute of Technology in Stockholm. This thesis is the result of a six-month project carried out in Ghana from September 2017 to February 2018 at the International Water Management Institute (IWMI). IWMI is an international non-profit scientific research organization which is a member of the Consultative Group on International Agricultural Research (CGIAR). IWMI's mission is to provide evidence-based solutions for the sustainable use of water and land resources in developing countries to enhance food security, reduce poverty, and maintain ecosystem health.

The present study fits in with a larger project conducted by IWMI in Ghana since 2013, i.e. the “Waste to Food” (WaFo) project, funded by the Bill & Melinda Gates Foundation, the UK Department for International Development, and Grand Challenges Canada. The WaFo project aims to provide solutions to scale out the recovery of nutrients and organic matter from faecal sludge for food production and sanitation in Ghana. One solution developed by IWMI and its partners, as part of the WaFo project, consists of co-composting faecal sludge with food waste into a marketable organic fertilizer, called *Fortifier™*. To produce and commercialise *Fortifier™* compost, a composting plant was built in Tema Metropolis in the Greater Accra Region and is now being operated by Jekora Ventures Ltd, a Ghanaian waste management company, as part of a public-private partnership with Tema Metropolis.

Besides co-composting faecal sludge and food waste, IWMI has been investigating other options to recover nutrients and organic matter from these waste streams. One solution suggested is the bioconversion of organic waste using the black soldier fly, a low-tech waste valorisation method which is being increasingly researched into, especially in the developing world. In this context, the present study was conducted to explore the opportunity to implement black soldier fly bioconversion process at the *Fortifier™* composting plant in order to yield additional revenues from the valorisation of faecal sludge and food waste.

Gabrielle Joly

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List of abbreviations and acronyms

BCR - Benefit Cost Ratio
BSF - Black soldier fly
CBA - Cost-benefit analysis
DW – Dry weight
FCR - Feed conversion ratio
FS - Faecal sludge
FW - Food waste
GHS - Ghanaian Cedis
IRR - Internal Rate of Return
IWMI - International Water Management Institute
JVL - Jekora Ventures Ltd
KTH: KTH Royal Institute of Technology
Min - Minimum
Max - Maximum
NPV - Net Present Value
Stdev - Standard deviation
USD - US Dollars
WW - Wet weight
- Number

Definitions

Faecal sludge - waste collected from on-site sanitation facilities. It consists of human excreta mixed with variable quantities of flush water and toilet paper, and eventually other waste types like plastic.

Food waste - food discarded at any stage of the food supply chain.

Low-cost system - system which relies on simple technology. In particular, a system which is not automated, and where environmental conditions are not digitally controlled.

On-site sanitation systems - they include non-sewered household and public toilets and latrines, aqua privies, and septic tank. They constitute the main system of sanitation in developing countries.

Waste valorisation: process that consists of converting waste into valuable products such as fuel, soil amendment, construction materials, feed products, etc.

Chapter 1: General Introduction

1.1 Background

Ghana, a rapidly growing and urbanizing middle-income country in West Africa, faces several major challenges, including improving its waste management system, increasing its agricultural productivity in a sustainable way, and providing livelihood opportunities to the poor and vulnerable. Ghana's total population more than doubled between 1984 and 2013, while, over the same period, the urban population more than tripled, outnumbering the rural population (World Bank, 2015). As a result of rapid population growth and urbanization, the amount of waste generated in Ghana has been rising steadily, placing an increasing pressure on an already overwhelmed waste management system (Boadi and Kuitunen, 2003; Thompson, 2010; Addaney and Oppong, 2015). Waste management is particularly problematic in urban areas like Accra, Ghana's capital city, which is home of about 16% of the Ghanaian population (Ghana Statistical Service, 2016) and one of the fastest growing metropolis in Africa (Thompson, 2010). In Accra, only 60% of household waste is collected, mainly in high- and middle-income neighbourhoods by private companies, while the remaining uncollected waste is openly burnt or dumped in streets, rivers, gutters, or holes, resulting in water, soil, and air pollution (Boadi and Kuitunen, 2003; Annepu and Themelis, 2013; Yoda et al., 2014; Addaney and Oppong, 2015). More generally, in Ghana's main cities, 20 to 40% of municipal solid waste is not collected (Impraim et al., 2014). In addition to solid waste, the management of faecal sludge from on-site sanitation facilities (i.e. non-sewered household and public toilets, latrines, septic tank, etc.) also constitutes a major challenge in Ghana, where most of the faecal sludge is currently disposed of directly into the environment, leading to the pollution of water resources and health risks due to the high pathogenic content of faecal sludge (Nartey, 2013; Nikiema et al., 2013b; Impraim et al., 2014).

Inappropriate waste management practices in Ghana have resulted in high occurrence of poor-sanitation related diseases, such as malaria, diarrhoea, intestinal worms, typhoid, and acute upper respiratory tract infections, which account for the vast majority of the reported cases at outpatient facilities across the country and constitute the main causes of death. Moreover, cholera outbreaks are regularly reported in the country (Boadi and Kuitunen, 2003; Thompson, 2010; Yoda et al., 2014; Addaney and Oppong, 2015). In addition to being collected, waste must be treated and valorised when possible in order to efficiently reduce associated health and environmental hazards. Besides, waste valorisation offers the opportunity to produce valuable products and thus generate revenues, which has the potential to incentive the waste management sector (Rao et al., 2017). This is particularly important in the Ghanaian context, where the implementation of an efficient waste management system is limited by the lack of financial resource (Addaney and Oppong, 2015). In this regard, organic waste represents a large fraction of the waste generated in Ghana. More than 60% of municipal solid waste is organic, the main category being food waste (Boadi and Kuitunen, 2003; Thompson, 2010; Miezah et al., 2015). Therefore, valorising organic waste can contribute to significantly improving the overall waste management system in Ghana.

Furthermore, organic waste valorisation enables the return of organic matter and valuable nutrients to the soil, thus improving soil fertility and crop productivity, which is crucial in Ghana, where most soils are poor in organic matter and nutrients, and increasing agricultural productivity has become a priority (Nartey, 2013; Impraim et al., 2014; Nikiema et al., 2014). Ghana, with its growing population and rising middle class, faces indeed the challenge of meeting an increasing demand for food and improving food security (AfDB, 2011; Darfour and Rosentrater, 2016; Murray, 2016). Today, about 5% of Ghana's population is food insecure and another 2 million Ghanaian are reported to be vulnerable to become food insecure (Darfour and Rosentrater, 2016). However, the development of the agricultural sector is constrained by the limited availability of affordable agricultural inputs as it relies largely on imported, expensive, and mostly unsustainable farming inputs.

Almost all the fertilizer used in Ghana for crop farming (mostly mineral fertilizer) is imported. As a result, fertilizer, needed to increase crop yields, which have remained low so far (FAO, 2005; Ayifli, 2017), is not affordable to many smallholder farmers, who make up most of the farming population and are the main producers of staple food crops (IFDC, 2000; Fuentes et al., 2012; Nartey, 2013; Darfour and Rosentrater, 2016; AFO, 2016). Similarly, the Ghanaian aquaculture sector must grow to meet the increasing local demand for fish, which represents the most important source of animal protein in Ghana. Yet, its development is limited by the high price of quality feed ingredients, which account for the high production costs of the aquaculture sector (FAO, 2005&2016; Devic et al., 2014; Fitches, 2016). Moreover, imported agricultural inputs, such as mineral fertilizer or conventional animal feed ingredients like fishmeal and soybean meal, are commonly associated with high environmental impacts, including eutrophication, soil impoverishment, deforestation, depletion of wild fish resources, carbon dioxide emissions, etc. (Tacon and Metian, 2008; Stamer, 2015; Lubkowski, 2016; Sprangers et al., 2017). This highlights the need to produce local, affordable and sustainable agricultural inputs, particularly fertilizer and animal feed. Besides improving food security, enhancing the availability of affordable agricultural inputs can improve the livelihood of Ghanaian farmers, most of whom are smallholder farmers. In addition, it can create economic opportunities for a large fraction of the population as almost 70% of Ghanaians are involved in the agricultural sector, either directly or indirectly along the value chain (Darfour and Rosentrater, 2016; Ayifli, 2017). More generally, creating livelihood opportunities is crucial in Ghana where more than one quarter of the population still lives under the poverty line of USD 1.25/day (FAO, 2015).

One solution that could address all these challenges at the same time consists of using abundant organic waste streams with high environmental impacts to locally produce quality animal feed ingredients and fertilizer in a cost-effective and environmental-friendly way. In this regard, insects, as natural converters of organic material, could play a major role (Rumpold et al., 2017). Especially, the black soldier fly (*Hermetia illucens*) has been portrayed as a beneficial insect in many respects. Black soldier fly (BSF) larvae efficiently convert a wide range of organic materials into organic fertilizer and an energy rich biomass (Caruso et al., 2013; Banks, 2014), which constitutes a valuable feed ingredients for various monogastric animal species, including poultry, pigs, and fishes (Hale, 1973; Newton et al., 1977; Bondary and Sheppard, 1987; St-Hilaire et al., 2007b). In addition, the BSF thrives in tropical climate like that of Ghana and does not constitute a nuisance nor a vector of disease, unlike other insects (Diener, 2010). Finally, by converting low-value organic waste into high-value insect protein and oil, BSF technology, which can be implemented at low-cost, has the potential to provide economic opportunities for both farmers and urban entrepreneurs (Diener et al., 2015a).

1.2 Aims and objectives

As a result, this study had two main aims. First, as organic waste valorisation by BSF is a relatively recent research topic, no comprehensive review of this waste valorisation technology is available to date. Therefore, the first aim of this study was to provide an extensive overview of BSF waste treatment method. Specific objectives pertaining to this aim were to (1.a) review the different aspects of BSF technology (technical, economic, environmental, legal, and social); (1.b) compare it to other options for organic waste valorisation; (1.c) describe and analyse concrete case studies of implementation; and (1.d) illustrate the status of the research and highlight needs for further research.

Secondly, as discussed above, BSF technology's characteristics makes it a promising organic waste treatment option in the Ghanaian context. Therefore, the second aim of this study was to investigate the technical and economic feasibility of implementing a low-tech BSF bioconversion system for faecal sludge and food waste in Ghana. With regard to this aim, specific objectives were as follows: (2.a) design and establish a small-scale BSF bioconversion system; (2.b) evaluate the performance of the rearing unit; (2.c) test the technical performance of the system for processing food waste and faecal sludge; and (2.d) analyse the economic viability of such system in the Ghanaian context. The aims and related objectives of the study are summarized in Table 1.1.

Table 1.1 - Overview of the aims and objectives of the study

Aims of the study	Specific objectives
Provide an extensive overview of BSF waste valorisation technology	Review the different aspects of BSF technology (technical, economic, environmental, legal, and social)
	Compare it to other options for organic waste valorisation
	Describe and analyse concrete case studies of implementation
	Illustrate the status of the research and highlight needs for further research
Investigate the technical and economic feasibility of implementing a low-tech BSF bioconversion system for faecal sludge and food waste in Ghana	Design and establish a small-scale BSF bioconversion system
	Evaluate the performance of the rearing unit
	Test the technical performance of the system for processing food waste and faecal sludge
	Analyse the economic viability of such a system in the Ghanaian context

1.3 Scope and limitations

1.3.1 Review of BSF waste treatment method

The review was based on literature produced from 1916 to October 2017. It focuses on the use of BSF for organic waste valorisation and does not discuss other applications of the BSF, such as forensic science. No specific context was focused on in order to provide an overview of BSF technology as comprehensive as possible. However, when relevant, the performance of the bioconversion process by BSF was compared for different contexts (e.g. tropical/temperate climate, developing/developed countries). Although case studies from different parts of the world were documented, most of them were in low and middle-income countries since most BSF facilities in high-income countries are commercial ventures which share very little information due to competitive reasons. Similarly, the review did not focus on a particular organic waste stream but instead compared the performance of BSF technology for different types of organic waste, including municipal and agro-industrial wastes.

The dimensions of BSF waste treatment method examined in the literature review were the following: technical, economic, environmental, legal, and social. Other aspects, such as political or ethical dimensions were not considered. As discussed in the next chapter, two main types of BSF bioconversion systems can be distinguished: systems relying on natural colonization by BSF and artificial rearing systems (Cicková et al., 2015; Lohri et al., 2017). As the former type of system is not suitable in the context of a controlled waste management operation, the literature review focused on the later types of systems, i.e. artificial rearing systems. Although a large number of studies on BSF waste valorisation and related topics were reviewed in order to give an extensive overview of BSF technology, this study did not intend to give a full account of all the literature produced on the subject. In addition, the documentation of the case studies was limited by the lack of independent sources of information. Finally, quantitative data regarding the process and the economic viability of the different cases studied were scarce, especially for the industrial-scale facilities.

1.3.2 Technical and economic feasibility study

On the other hand, the feasibility study focused on the Ghanaian context and more particularly on the context of Greater Accra region, where the field work was conducted from December 2017 to February 2018. The study concerned a low-tech BSF bioconversion system, i.e. a system where a limited control was exercised on environmental parameters (e.g. temperature, humidity, light, etc.). The feasibility of implementing such system was analysed from both the technical and economic perspectives. Other dimensions such as environmental, social or legal aspects were not investigated. In addition, the technical and economic feasibility was examined for two particular waste streams, namely food waste and faecal sludge, since they are particularly abundant waste sources in the Greater Accra region and, in addition to being rich in nutrient, are associated with significant health and environmental impacts if not treated appropriately.

Due to time and financial constraints, the technical feasibility of valorising food waste and faecal sludge using a low-tech BSF bioconversion system in Ghana was evaluated in terms of a limited number of parameters. Especially, only performance indicators pertaining to biomass production and waste reduction were considered, while the characteristics of the bioconversion products, such as the nutritional properties of the larval biomass, and nutrient content of the waste residue could not be analysed. In addition, the technical study was based on a small number of replications. Similarly, rearing performance of the breeding system established could be recorded only over one lifecycle of the BSF. As for the economic analysis, it was constrained by the limited availability of financial data regarding the BSF process, as well as difficulties to access quantitative data pertaining to the Ghanaian context. In addition, it was based on a number of simplifying assumptions and a generalization of the experimental results and data from *Fortifier™* composting plant's case study.

1.4 Structure of the report

The rest of the report is divided into four chapters. Chapter 2: is dedicated to the review of organic waste valorisation by BSF. In Chapter 3:, methods for the technical feasibility study are described and its results are presented and discussed. Then, the economic viability of implementing a low-cost BSF bioconversion system in Ghana is analysed in Chapter 4:. Finally, Chapter 5: consists of a brief conclusion of the study.

Chapter 2: Valorising Organic Waste using the Black Soldier Fly (*Hermetia illucens*) - a Comprehensive Review

Due to its length, the full review of BSF technology, written as part of this study, could not be included in the present report. Therefore, this chapter consists of a summary highlighting the essential information of the review.

2.1 Methods for the review

This review of BSF technology for organic waste valorisation is based on an extensive scientific literature review, field visits of BSF systems in Sweden and Ghana, and information from experts working with this technology. A thorough literature search was carried out through June 2017 using the Web of Science and Science Direct databases, Google Scholars, as well as specific libraries, such as Wiley Online Library, Sage Journals, and Springer Link. The search strings used for the literature review included “black soldier fly”, “*Hermetia illucens*”, and “organic waste”. Additional publications were then identified based on the references used in the articles found through the database search. In total, 90 studies on BSF technology were selected and reviewed. In addition, numerous additional relevant sources were used to supplement certain information about specific topics. In addition, BSF systems in Ghana and Sweden were visited and actors working with BSF technology were interviewed in order to provide concrete case studies of the implementation of a BSF system.

This analysis was guided by the following research questions:

- How does the waste treatment by BSF work?
- How to implement it?
- How does such a system perform technically, economically, and environmentally?
- What are the prospects and constraints associated with the implementation of BSF technology?

2.2 Results for the review

2.2.1 The black soldier fly (BSF)

- Specie and distribution

The black soldier fly (*Hermetia illucens*), also known as latrine larvae, is a dipterian from the Stratiomyidae family (Diener, 2010; Caruso et al., 2013; Lohri et al., 2017; Dortmans and al., 2017). It is originally native to America but has spread to other parts of the world through the transport of goods and human migrations (James, 1935; Callan, 1974; Leclercq, 1997). Today, it is commonly found in tropical and warm temperate regions between the 45°N and 40°S latitudes, as shown in Figure 2.1 (Diener, 2010; Caruso et al., 2013; Lohri et al., 2017; Dortmans and al., 2017).



Figure 2.1 - Prevalence of the black soldier fly
Source: Dortmans et al. (2017)

- Lifecycle

The BSF has a rather short lifecycle of about 6-7 weeks (Tomberlin et al., 2002; Alvarez, 2012; Caruso et al., 2013; Dortmans, 2015). However, its lifecycle length depends on the environmental conditions as the BSF can slow down its activity to survive under unfavourable conditions (Banks, 2014). Five main stages can be distinguished in the BSF's lifecycle: 1) egg, 2) larval, 3) prepupal, 4) pupal, and 5) adult (Banks, 2014; Oliveira et al., 2015), as illustrated in Figure 2.2. The larval and pupal stages make up most of the lifecycle's duration, the egg hatching and adult stages being in comparison relatively short. Several characteristics of the black soldier fly make this insect particularly attractive to valorise organic waste. The voracious appetite of the BSF larvae for decaying organic matter enables it to efficiently convert a wide range of organic waste. The shortness of the BSF lifecycle allows its frequent reproduction, therefore ensuring a steady source of larvae to convert the organic waste, as well as a reliable supply of energy-rich larvae that can be used as animal feed. Besides, it is a resilient organism, which facilitates its rearing and makes its use in waste treatment not too constraining. Finally, by crawling naturally out of the waste, the prepupae can be very easily harvested.

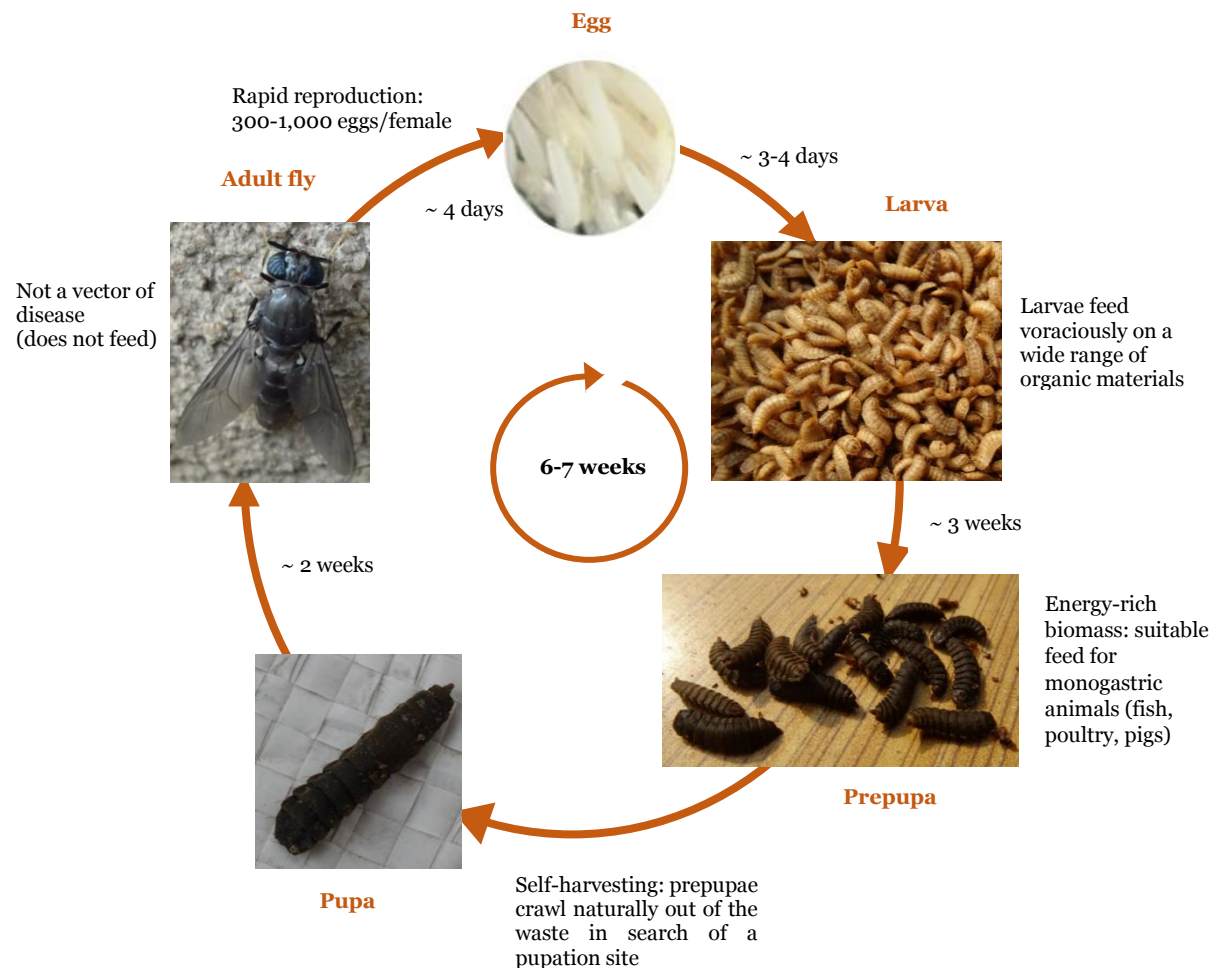


Figure 2.2 - Lifecycle of the BSF
Source of the pictures: Gabrielle Joly and dailydump.org

2.2.2 Waste treatment by BSF

In a nutshell, waste treatment by BSF consists of feeding organic waste to BSF larvae in order to produce energy-rich larvae and organic fertilizer. To take advantage of the natural features of BSF in waste management, its natural lifecycle must be engineered to optimize waste reduction and biomass production. Therefore, this section addresses the technical aspect of BSF technology, describing how it works and how it can be optimized.

Today, two main types of BSF waste treatment systems can be distinguished, namely systems relying on natural colonization by BSF and artificial rearing systems (Cicková et al., 2015; Lohri et al., 2017). Systems relying on BSF natural population were historically developed for manure management (Sheppard, 1983; Sheppard et al., 1994). Today, such systems are mainly used at the household level, typically for backyard applications (Lohri et al., 2017). While such systems are relatively cheap and easy to implement, they are unsuitable in the context of a controlled waste treatment facility (Cicková et al., 2015; Lohri et al., 2017). Therefore, recent literature mostly focuses on artificial rearing systems, which typically include a rearing unit, or 'nursery', where BSF are bred to produce juvenile larvae, which are used to process the incoming waste in a separate unit, i.e. the waste treatment unit (Diener et al., 2015a; Lohri et al., 2017; Dortmans et al., 2017). Such systems are more expensive and complex than those depending on natural BSF population, but allow a controlled operation, stable production, and optimized waste reduction and biomass production (Cicková et al., 2015; Lohri et al., 2017). Therefore, the present review focuses on this latter type of system.

The BSF treatment process can be typically broken into the following main units: 1) waste pre-processing, 2) BSF rearing, 3) waste treatment, 4) product harvesting, and 5) post-treatment of the products (Dortmans et al., 2017). Figure 2.3 illustrates the different units of a typical BSF treatment facility.

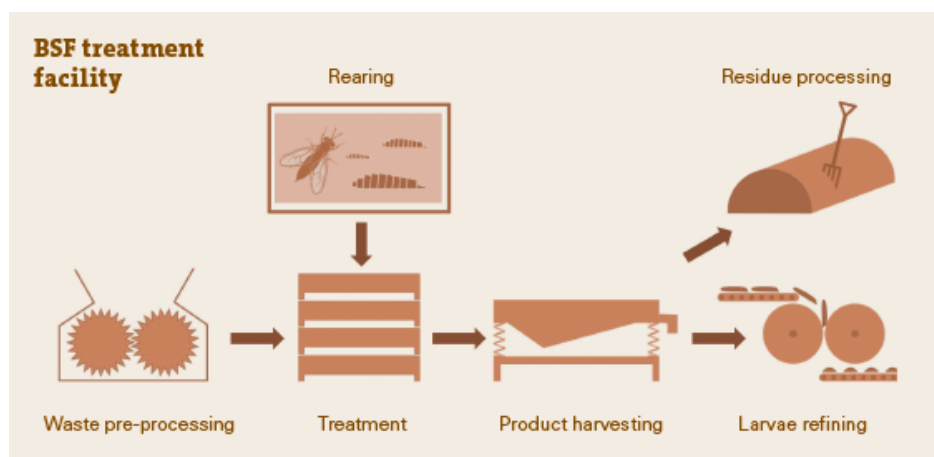


Figure 2.3 - Overview of the BSF waste treatment process
Source: Dortmans et al. (2017)

- Waste pre-processing

The feedstocks reported in the literature to be suitable for BSF treatment include mixed municipal organic waste (Diener et al., 2011), food, restaurant, and market waste, such as fruit and vegetable waste (Nguyen et al., 2015; Parra Paz et al., 2015; Saragi and Bagastyo, 2015; Cheng and Lo, 2016; Leong et al., 2016), animal manure, such as poultry, cow, and pig manure (Sheppard et al., 1994; Yu et al., 2011; Myers et al., 2008; Li et al., 2011a; Newton et al., 2005; Nguyen et al., 2015), human faeces and faecal sludge (Lalander et al., 2013; Banks, 2014; Banks et al., 2014), human and animal cadavers (Dunn, 1916; Nguyen et al., 2015), agro-industrial waste, such as food processing waste (Lardé, 1989; Caruso et al., 2013; Dortmans and al., 2017; Mohd-Noor et al., 2017), spent grains (Dortmans and al., 2017), slaughterhouse waste (Dortmans and al., 2017), and fish waste (Nguyen et al., 2015; Saragi and Bagastyo, 2015; St-Hilaire et al., 2007b). Despite the flexibility of BSF larvae regarding the feedstock, key parameters influence the ability of BSF larvae to process a material. They are presented in Table 2.1.

Table 2.1 - Key parameters for the feedstock and optimal values

Parameters pertaining to the feedstock	Optimal values	Suggested pre-processing methods for optimisation	References
Moisture content	60 - 90% (wet weight)	Dewatering, water addition and/or mixing different waste types	Cammack and Tomberlin (2017), Cheng et al. (2017), Dortmans et al. (2017), Lohri et al. (2017)
Particle size	1-2 cm	Shredding	Dortmans et al. (2017), Lohri et al. (2017)
Nutrient content	Feedstock rich in protein and carbohydrates (e.g. 21% protein and 21% carbohydrate); Suitable C/N ratio: 10-40 (optimal nutrient balance not established)	Mixing different waste types	St-Hilaire et al. (2007a), Gobbi et al. (2013), Saragi and Bagastyo (2013), Lalander et al. (2015), Cammack and Tomberlin (2017), Dortmans et al. (2017), Lohri et al. (2017), Rehman et al. (2017a&b).
pH	5-8 (suitable values)	Mixing different waste types	Caruso et al. (2013), Dortmans (2015), Lalander et al. (2015), Rehman et al. (2017a&b)
Fibre content	Not too high (no optimal value established)	Pre-fermentation	Zheng et al. (2012a), Caruso et al. (2013), Lohri et al. (2017), Mohd-Noor et al. (2017), Rehman et al. (2017a).
Structure	Sufficient structure to allow the larvae to move through the feedstock, consume it and breathe	Addition of matrix material, such as pine shavings or crushed charcoal	Barry (2004), Perednia (2016)

- **BSF rearing**

A BSF rearing unit consists of a nursery where adult flies are bred in captivity to mate and lay eggs, which are incubated until they hatch into larvae. Larvae are then fed until they turn into prepupae and then pupae. The flies emerging through pupation are in turn used to produce eggs again and thus maintain the colony. The main purpose of the rearing unit is to provide a reliable supply of juvenile larvae to convert the organic waste to be treated. Optimal conditions to rear the BSF at the different stages of its lifecycle and operational designs proposed in the literature are summarized in Table 2.5. In addition, Table 2.2 presents values for various rearing performance indicators recorded in two Indonesian facilities.

Table 2.2 - Comparison of the rearing performance of two Indonesian BSF facilities

Performance indicators	Values reported by Dortmans et al. (2017)	Values reported by Caruso et al. (2013)
Hatching rate	70%	80%
Larval survival rate	70%	60 %
Adult emergence rate	80%	90%
Oviposition rate	350 eggs/female	18 eggs/female ¹

¹ Calculated based on the value provided by Dortmans et al. (2017) for the average weight of an egg (25 µg). As pointed out by Caruso et al. (2013), this value is very low compared to values reported in the literature, which could be explained by a range of physical, behavioural, abiotic or technical factors.

- Waste treatment

The waste treatment itself consists of feeding juvenile larvae produced in the rearing unit with the organic waste to be processed. The larvae fed with the waste grow into energy-rich prepupae while reducing the waste (Dortmans et al., 2017). Optimal operating conditions for BSF waste treatment are summarized in Table 2.3, while the main operational designs proposed in the literature for BSF reactors are described in Table 2.4.

Table 2.3 - Optimal operating conditions for BSF waste treatment

Operating parameter	Optimal value	References
Feeding rate	60 – 175 (mg/larva/day, 60% moisture content) depending on the waste type	Diener et al. (2009b)
Larval density	1.2 – 5 larvae/cm ²	Parra Paz et al. (2015)
Waste layer thickness	< 7.5 cm or < 15 cm if matrix materials are added to the waste	Perednia (2016), Yang (2017)

Table 2.4 - Operational designs proposed in the literature

	Characteristics	References
Type	Individual containers or larger basins	Tomberlin et al. (2002), Newton et al. (2005),
Volume	40 – 400 L	Diener et al. (2011), Caruso et al. (2013), Devic (2014), Charton et al. (2015), Lalander et al. (2015),
Material	Plastic, metal, or concrete	Mutafela (2015), Popoff and Maquart (2016a&b),
Special features	Drainage system, system to prevent disturbance from other insects or predators	Dortmans et al. (2017)

Table 2.5 - Optimal rearing conditions and operational designs suggested in the literature

Lifecycle stage	Optimal operating conditions				Suggested operational Designs	References
	Temperature	Humidity	Light	Diet	Other	
Eggs	Constant temperature (e.g. ~ 27°C)	> 60%	Dark environment	None	-	Sheppard et al. (2002), Zhang et al. (2010), Diener et al. (2011), Alvarez et al. (2012), Holmes et al. (2012), Mutafela (2015)
Juvenile larvae (4-6 day-old)	Constant temperature in the 24-33°C range	Relatively constant humidity level	Dark environment	Special diet (e.g. wheat bran, rabbit, or chicken feed) with enough structure	-	Sheppard et al. (2002), Diener et al. (2011), Caruso et al. (2013), Dortmans et al. (2017), Yang (2017)
Larvae	24-33°C	Literature focuses on the moisture content of the feedstock	Dark environment	Well-defined diet or organic waste to be treated	-	Sheppard et al. (2002), Tomberlin et al. (2002), Alvarez (2012), Caruso et al. (2013), Harnden and Tomberlin (2016), Dortmans et al. (2017)
Prepupae/Pupae	In the same range as the larval stage (24-33°C)	60-70%	Dark environment	None	Pupation medium (e.g. wood chips, coco peat, compost) exhibiting a moisture level of 50-85% and a depth of 15-20 cm.	Newton et al. (2005), Diener et al. (2011), Alvarez (2012), Caruso et al. (2013), Banks (2014), Mutafela (2015), Lin (2016), Nakamura et al. (2016), Dortmans et al. (2017)
Adults	25-32°C	> 60%	Morning sunlight	None but providing water with sugar is recommended	Sufficient space to mate in flight. High fly density (5000 flies/m ³). Plant to favour lekking.	Booth and Sheppard (1984), Holmes et al. (2012), Sheppard et al. (2002), Tomberlin and Sheppard (2002), Zhang et al. (2010), Diener et al. (2011), Alvarez (2012), Caruso et al. (2013), Mutafela (2015), Nakamura et al. (2016), Dortmans et al. (2017)

Table 2.6 shows values reported in the literature for various indicators, characterizing the performance of BSF waste treatment process, for different feedstocks.

Table 2.6 - Performance of the BSF process for different feedstocks

Feedstock	Waste reduction (%)	Mean larval weight (mg)	Larval development time (days)	Bioconversion (%)	Food conversion ratio	References
Pig manure	56 (DW)	113 (WW)	25 - 46	4 (DW)	10 (DW)	Newton et al. (2005), Nguyen et al. (2013), Banks et al. (2014)
Dairy manure	33 - 58 (DW)	137-179 (WW)	26-30	2-4* (DW)	-	Myers et al. (2008)
Chicken manure	50 (WW)	220 (WW)	-	4 (WW)	13 (WW)	Sheppard et al. (1994), Banks et al. (2014)
Dairy manure and chicken manure	43-55 (DW)	60-100 (WW)	18-22	4-10 (DW)	6-10 (DW)	Rehman et al. (2017a)
Human faeces	25 - 55 (WW)	194-315 (WW)	-	2-22 (WW)	2-16 (WW)	Bank et al. (2014)
Municipal organic waste	66-79 (DW)	138-220 (WW)	-	12 (DW)	15 (DW)	Diener et al. (2011), Banks et al. (2014)
Kitchen waste	-	173 (WW)	20 - 33	-	-	Nguyen et al. (2013)
Restaurant waste	-	154 (WW)	19	-	-	Spranghers et al. (2017)
Fruit and vegetable	43-64 (DW)	123 (WW)	22 - 40	-	-	Nguyen et al. (2013), Saragi and Bagastyo (2015)
Vegetable waste	-	140 (WW)	16	-	-	Spranghers et al. (2017)
Fish waste	19 - 54 (DW)	143 (WW)	20 - 36	-	-	Nguyen et al. (2013), Saragi and Bagastyo (2015)
Overall range	19-79	60-315	16-46	2-22	2-16	

* Value obtained by using an equation

DW: dry weight; WW: wet weight

- Harvesting and post-treatment of the products

The BSF process yields two main products, namely energy-rich larvae, and the waste residue, whose properties and applications are summarized in Table 2.7.

Table 2.7 - Summary table of BSF products' properties and applications

	Larvae	Waste residue
Yield	40-118 kg of larvae/tonne of waste (DW)	210-810 kg of waste residue/tonne of waste (DW)
Properties	High protein (40% DW) and lipid content (35% DW). Relatively rich in Ca, P, and K. Main fatty acids: lauric acid, palmitic acid, and oleic acid. Main essential amino acids: lysine, valine, and leucine.	The waste residue still contains valuable nutrients, including increased concentration of ammonium nitrogen. C/N ratio depends on the initial C/N ratio of the input waste. pH between 7 and 8. Compost obtained is immature.
Safety	The level of most chemical contaminants are lower than those recommended. The only chemical risk identified pertains to the bioaccumulation of cadmium in larvae. There is also a risk of presence of pathogens in larvae reared on animal or human waste despite the antibacterial properties of the larvae	BSF waste treatment removes, in animal and human waste, bacteria from the Enterobacteriaceae family (<i>Salmonella</i> spp. and <i>E. Coli</i>) under sufficient temperature (27-32°C) and alkaline conditions but has no effect on the destruction of other pathogens, such as <i>Enterococcus</i> spp., bacteriophage, or <i>Ascaris suum</i> ova. BSF treatment also accelerates the degradation of different types of pharmaceuticals and pesticides in the waste.
Applications	The main application for BSF larvae is their use as feed ingredients for monogastric animals. The oil extracted from the larvae can also be used to produce biodiesel and the chitin contained in the exoskeleton of the larvae can be sold as a chelating agent.	Fertilizer
Post-treatment	Sanitization (e.g. boiling), drying, lipid extraction, etc.	Thermophilic composting or vermicomposting
References	Hale (1973), Newton et al. (1977&2005), Bondari and Sheppard (1981&1987), Erickson et al. (2004), St-Hilaire (2007a&b), Diener (2010), Diener et al. (2011&2015b), Li et al. (2011b), Sealey et al. (2011), Zheng et al. (2012a&b), Caruso et al. (2013), Finke (2013), Lalander et al. (2013&2016), Banks et al. (2014), Lock et al. (2014), Makkar et al. (2014), Charlton et al. (2015), Leong et al. (2015&2016), Park et al. (2015), Tran et al. (2015), Cummins Jr et al. (2017), Devic et al. (2017), Dortmans et al. (2017), Gao et al. (2017), Lui et al. (2017), Rehman et al. (2017a), Liland et al. (2017), Schiavone et al. (2017), Sprangers et al. (2017)	Erickson et al. (2004), Newton et al. (2005), Liu et al. (2008), Choi et al. (2009), Diener et al. (2011), Green and Popa (2012), Lalander et al. (2013&2015&2016), Banks et al. (2014), Adeku (2015), Dortmans (2015), Saragi and Bagastyo (2015), Murray (2016), Dortmans et al. (2017), Lohri et al. (2017), Quilliam et al. (2017), Rehman et al. (2017a)

DW: dry weight; Ca: Calcium; P: Phosphorus; K: Potassium

2.2.3 Economic, environmental, legal, and social dimensions of the BSF technology

- Economic dimension

Few studies address the economic dimension of the BSF technology, as most research focus on the biological aspect of the process. Moreover, the studies that do analyse the economic viability of the BSF technology consist mostly of extrapolations from experimental or pilot systems to commercial facilities or are based on case studies with numerous simplifying assumptions (Cicková et al., 2015). Table 2.8 provides an overview of the data pertaining to BSF technology's economic performance reported in the literature.

Table 2.8 - Summary table of economic benefits and costs associated with a BSF facility

	Parameter	Value	Comments	References
Economic benefits	Price for the larvae (animal feed) (USD per tonne of larvae meal)	Range: 200-2,000; Average: 965	The value depends on the market targeted (e.g. aquaculture or poultry feed) and the grade of the product (degree of refining)	Tomberlin and Sheppard (2001), Newton et al. (2005), Diener et al. (2009a), OvrSol (2010), Agrawal et al. (2011)
	Annual revenue from the sales of larvae as animal feed ingredients (USD/year/tonne daily input)	Range: 6,500 (19 kg of larvae/tonne/day, DW) ^a – 20,000 (50 kg of larvae/tonne/day, DW) ^b ; Average: 13,250	Besides the selling price, this value depends on the performance of the BSF facility, i.e. the daily weight of larvae produced per tonne of waste treated (indicated in bracket)	a: Popoff and Maquart (2016b) b: Diener et al. (2009a),
	Annual revenue from the sales of the waste residue as biofertilizer (USD/year/tonne daily input)	6,300 (yield: 230 kg of compost/tonne of waste/day)	The ability of the waste residue to contribute to the revenue of a BSF treatment facility is questioned by some authors, while other authors pointed out the difficulty to estimate a price for this product as there is no established market for vermicompost.	Popoff and Maquart (2016b)
	Cost-savings on organic waste disposal	75% for swine manure, 85% for cow manure, 20% for food waste	All these studies were conducted in North America	Barry (2004), Newton et al. (2005), Amatya (2008)
	Space requirement (m ² /tonne daily input)	140-640 for medium-scale facility and 40-50 for large scale facilities	Medium-scale capacity: 100 kg – 10 tonnes of waste/day Large-scale capacity: > 100 tonnes of waste/day	Diener et al. (2009a) and data provided in the case studies
Costs	Infrastructure costs (USD/tonne daily input)	13,000-18,000 for medium-scale facility and 32,000-75,000 for large scale facilities	-	Diener et al. (2009a) and data provided in the case studies
	Infrastructure costs (USD/m ²)	30-35 for medium-scale facility and 900-1,400 for large scale facilities	-	Diener et al. (2009a) and data provided in the case studies
	Total investment costs (USD/tonne daily input)	23,000 - 28,000	Data available only for developing countries	Diener et al. (2009a) and Popoff and Maquart (2016b)
	Labour requirement (number of operator/tonne daily input)	1-3 for medium-scale facility and 0.3-0.4 for large scale facilities	-	Diener et al. (2009a) and data provided in the case studies
	Labour cost (USD/tonne daily input)	1,900 (160) -7,700 (390)	The numbers in brackets are the average wages on which the calculation of the labour cost is based on (in USD/month)	Diener et al. (2009a) and Popoff and Maquart (2016b)
	Labour cost (USD/ kg of larvae)	1.1-1.4 (wet weight) 0.43-0.85 (dry weight)		Diener et al. (2009a), Caruso et al. (2013), Popoff and Maquart (2016c)
	Water and energy costs (USD/ m ² /year)	0.45-4.6 in tropical countries; 33 in Northern Countries		Diener et al. (2009a), Alvarez. (2012), Popoff and Maquart (2016c)
	Total running costs (USD/year/tonne daily input)	~ 12,000	Data available only for developing countries. Running costs are reported to be 2 to 4 times lower than investment costs	Diener et al. (2009a) and Popoff and Maquart (2016b)
	Overall performance (yearly profit)	Food waste: 90 USD/tonne/year in Canada; BSF manure management system: 100 to 280 USD/cow/year, 25,000 USD/ poultry house/year in the US; Faecal sludge: 116,000 USD /year for processing the waste from 3 latrines/day in Tanzania		Newton et al. (2005), Amatya (2009), Agrawal et al. (2011), Alvarez (2012)

- Environmental dimension

Table 2.9 summarizes the main environmental benefits and adverse impacts associated with the BSF technology.

Table 2.9 - Environmental performance of BSF waste treatment process

	Characteristics		References
Environmental benefits	Larvae as an alternative to unsustainable animal feed products	Producing insect-based meals from high-impacting waste streams or low value food processing by-products is two to five times more environmental-friendly than manufacturing conventional feed products	Smetana et al. (2016)
	Nutrient leakage reduction	Reduction of the pollution potential of waste by 50-60%	Newton et al. (2005) van Huis et al. (2013)
	Energy related benefits	The production of BSF larvae-based biodiesel exhibits a higher conversion efficiency (460 L/tonne of larvae, dry wet) and yield (50-30 ML/ha/year) compared to common biodiesel feedstocks	FAO (2008), Li et al. (2011b), Zheng et al. (2012a&b), Shikida et al. (2014)
	Odour reduction	Odour reduction due to short processing time, reduction of bacterial activity, aerating and drying of the waste by larvae	Newton et al. (2005 & 2008), Diener, (2010), van Huis et al. (2013)
Negative environmental impacts	Main adverse impacts: energy consumption for post-processing the products and waste transport		Salomone et al. (2017)
Overall environmental performance	The impacts of processing 1 tonne of food waste into larvae protein for aquaculture and larvae oil for biodiesel production in Italy are estimated at 30.2 kg CO ₂ eq in terms of Global Warming Potential, 215.3 MJ in terms of Energy Use, and 0.661 m ² of arable land in terms of Land Use		Salomone et al. (2017)

- Legal dimension

The main legal issue regarding BSF concerns the use of insects as feed ingredients in the animal production industry. Many countries do not have any regulation regarding animal feeding with insect proteins (Caruso et al., 2013; van Huis et al., 2013; Cickova et al., 2015). Therefore, Table 2.10 provides an overview of the current legislation pertaining to the use of BSF larvae as animal feed in different parts of the world.

Table 2.10 - Legislation on the use of BSF larvae as animal feed

Context	Legislation regarding the use of BSF larvae proteins as animal feed	References
EU	The use of feed ingredient derived from BSF larvae has been recently authorised in aquaculture, but most conventional waste streams are prohibited to be used as feedstock to rear the larvae. The use of BSF larvae to feed livestock animals is still banned.	Caruso et al. (2013), van Huis et al. (2013), Cickova et al. (2015), Leung (2016&2017), FEFAC (2017), IPIFF (2017)
North America	Some BSF larvae-based feed ingredients have been approved as feed for certain fish and poultry species in the US and Canada	
Developing countries	The use of insect protein to feed animals is often tolerated, resulting in less legal barriers	

- Social dimension

Table 2.11 highlights the main social issues and benefits associated with BSF technology.

Table 2.11 - Social issues and benefits associated with BSF technology

Aspect	Description	References
Public health	The BSF is a non-pest insect which does not constitute a vector of disease. BSF repel other common fly species, such as house flies. Exceptional cases of myiasis caused by BSF larvae have been reported in tropical countries. BSF larvae reduce some pathogens in the waste. Release of volatile by-products and noxious gases during the bioconversion of organic waste by BSF larvae could constitute a health hazard for the staff working at BSF facilities.	Furman et al. (1959), Sheppard (1983), Bradley and Sheppard (1984), Sheppard et al. (1994), Adler and Brancato (1995), Lee et al. (1995), Newton et al. (1995), Sheppard et al. (1998), Gonzales and Oliva (2009), Diener (2010&2017), Olivier et al. (2011), Caruso et al. (2013), van Huis et al. (2013), Cicková et al. (2015), Oliveira et al. (2015)
Social benefits	BSF technology could provide livelihood opportunities to farmers and entrepreneurs all over the world, and especially in developing countries. By yielding protein-rich larvae that can be used as animal feed and a waste residue that can act as a fertilizer, BSF technology could contribute to food security.	Diener et al. (2011&2015a), Makkar et al. (2014), van Huis et al. (2013)
Social acceptance	According to several studies, consumers seem to have a positive attitude toward the inclusion of BSF larvae-based ingredients in the diet of farmed animals and be willing to eat meat from animals that were fed with BSF larvae ingredients. However, consumer acceptance may depend on the type of waste used to feed the larvae.	FERA (2016), PROteINSECT (2016), Popoff et al. (2017)

In Table 2.12 (Box 2.1), BSF waste treatment method is compared to other organic waste valorisation techniques, such as composting, anaerobic digestion, and vermicomposting.

Box 2.1 - BSF treatment compared to other organic waste treatments

Table 2.12 - Comparison between BSF technology and other organic waste treatment options	
Aspect	BSF treatment compared to other organic valorisation techniques
Feedstock	Besides materials exhibiting a high lignocellulosic content, most organic waste can be processed through BSF technology. In addition, nutrient balance and pH are not essential. Thus, BSF technology is more flexible in terms of input compared to anaerobic digestion and vermicomposting, for which feedstocks with a narrower range of C/N balance are suitable.
Resource requirements	When using vertical stacking, BSF process requires little space (e.g. ~150 m ² /ton of daily input in medium-scale facilities and 40-50 m ² /ton of daily input in large scale facilities) compared to composting (200-250 m ² /ton of daily input) and vermicomposting (800 m ² /ton of daily input or 200 m ² /ton of daily input with vertical stacking). Energy requirements depends on climatic conditions. In Northern countries, the process may be relatively energy-consuming compared to other organic waste treatments. On the other hand, in tropical climates, no environmental control and thus much less energy is required. However, drying the larvae, depending on the drying technology used, may significantly increase energy requirements of BSF treatment.
Processing time	Waste processing time by BSF is very short (10-14 days, based on the case studies) compared to composting (> 90 days for mature compost), vermicomposting (>45-60 days), and anaerobic digestion (30 days). However, the waste residue obtained may need to undergo a maturation phase.
Hygienisation	Like vermicomposting and anaerobic digestion, BSF treatment does not allow complete inactivation of pathogens, while composting does thanks to high temperature inside the compost piles.
Emissions	Compared to composting, the BSF bioconversion process results in 70% less CO ₂ emissions. In addition, there is no risk of methane leakages, like there is for anaerobic digestion. Finally, BSF process is not odorous as BSF larvae reduce and sometimes even eliminate the foul odour from decomposing organic.
Skill requirement	As composting and vermicomposting, BSF treatment only requires simple labour skills, while anaerobic digestion entails technical skills and trained technicians.
Products (value and yield)	An advantage of BSF process is that it yields two valuable products, like vermicomposting. In addition, larvae-derived feed products are associated with a potential significant market demand from the animal production industry and a relatively high-value, which may give BSF treatment a greater opportunity to incentivize waste management, compared to the other technologies.
Investment costs	Compared to anaerobic digestion, BSF treatment is a low-cost technology.
Regulatory hurdles	Regulatory hurdles related to the use of insect-based feeds in animal production is probably the main drawback associated with BSF technology, while regulation is a less important issue for other treatment methods.
Maturity of the technology	Compared to the other treatment methods, BSF technology is relatively immature and cases of implementation still scarce.
Based on information provided by Komakech et al. (2015), Lohri et al. (2017), Perednia (2017) and data from the case studies	

2.2.4 Implementation of the BSF technology: case studies

Today, two main trends regarding the implementation of the BSF technology can be distinguished. On the one hand, large-scale industrial facilities, processing up to several hundreds of tonnes of waste per day and producing dozen of tonnes of larvae-based feed ingredients, are already being operated in South-Africa, Canada, the USA, Netherlands, and China. These facilities focus primarily on the production of proteins for the animal feed industry, taking advantage of potential great market opportunities (Diener et al., 2015a). The examples of AgriProtein in South-Africa and Enterra Feed in Canada were analysed as part of this study. On the other hand, many small-scale BSF systems have been implemented at the household level by enthusiastic individuals primarily motivated by the waste treatment aspect. In this regard, several blogs and discussion forums, where experiences and designs are shared, can be found on the internet (e.g. blacksoldierflyblog.com, blacksoldierflyfarming.com). In the middle of the spectrum, medium-scale BSF facilities treating hundred kilos to 10 tonnes of waste per day are very scarce (Diener et al., 2015a). In addition, the few that do exist have been built as part of research projects, like FORWARD in Indonesia and Ento-Prise in Ghana and have not yet succeeded to reach profitability (Murray, 2016; B. Dortmans, personal communication, 28 September 2017). To bridge this gap and ensure both an efficient waste management and profitable protein production system, Diener et al. (2015a) suggested a semi-centralised organisation, which combines the advantages of centralised large-scale facilities focusing on protein production and the benefits of decentralised waste management systems. It consists of a centralised BSF rearing and refinery facility working with a network of decentralised waste treatment units located near waste generation sources (see Figure 2.4). A similar organisation was suggested by Campbell (2013) to make BSF technology more accessible for on-farm manure management by livestock farmers.

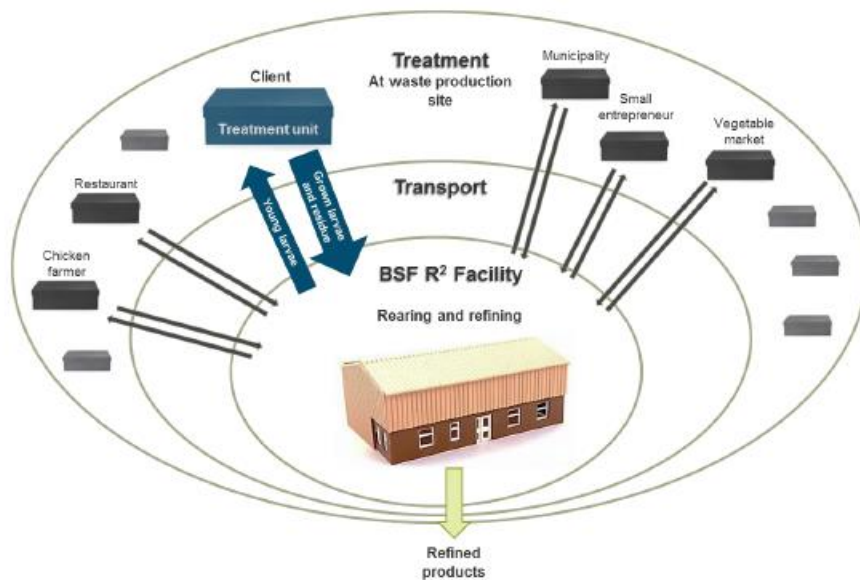


Figure 2.4 - Semi-centralised system proposed by Diener et al. (2015a)
Source: Diener et al. (2015a)

Table 2.13 provides an overview of the case studies developed as part of this study and Box 2.2 highlights the main lessons drawn from these case studies.

Table 2.13 - Overview and comparison of the case studies documented

Case study	FORWARD	AgriProtein	Ento-Prise	Enterra Feed
Location	Indonesia	South-Africa	Ghana	Canada
Context	Lower middle-income country, tropical climate	Upper middle-income country, temperate climate	Lower middle-income country, tropical climate	High-income country, temperate climate
Case type	Research project	Commercial venture	Research project	Commercial venture
Scale	Medium-scale	Large-scale	Medium-scale	Large-scale
Waste input type	Market waste	Food industry, restaurant, and municipal organic wastes	Market waste	Pre-consumer food waste
Waste processing capacity	3 tonnes of waste/day	250 tonnes of waste/day	330 kg of waste/day	100 tonnes of waste/day
Products	Whole and dried larvae, biofertilizer, and BSF rearing starter kit	Dried and defatted BSF larvae, larvae oil, and biofertilizer	Dried larvae and biofertilizer	Whole dried larvae, larvae meal, larvae oil and biofertilizer.
Production capacity	Unknown	7 tonnes of insect meal, 3 tonnes of oil and 20 tonnes of biofertilizer per day	About 6 kg of dried larvae per day and 75 kg of compost per day	7 tonnes per day of protein and oil feed ingredients and 8 tonnes per day of biofertilizer
Facility area	424 m ² (~140 m ² to produce 1 tonne/day)	9,000 m ² (~ 40 m ² to produce 1 tonne/day)	212 m ² (~640 m ² to produce 1 tonne/day)	5,300 m ² (~50 m ² to produce 1 tonne/day)
Number of operators/employees	3 operators (1 operator to produce 1 tonne/day)	90 employees (0.4 employees to produce 1 tonne/day)	1 operator (3 operators to produce 1 tonne/day)	32 employees (0.3 employees to produce 1 tonne/day)
Construction cost of the facility	Not available	USD 8 million (~USD 32,000 per tonne of daily waste treatment capacity)	USD 6,090 (~USD 20,000 per tonne of daily waste treatment capacity)	USD 7.5 million (~USD 75,000 per tonne of daily waste treatment capacity)
Waste processing time	12 days	10 days	10 days	14 days
References	Bucher and Peterhans (2016), Verstappen et al. (2016), Wijaya (2016), Dortmans (2017) (Mr. B. Dortmans, personal communication, 28 September 2017), Dortmans et al. (2017), Eawag (2017a&b)	Heffernan (2013), Iwuoha (2014), Pozzebon (2015), Burwood-Taylor (2016), AgriProtein, (2017a,b,c,d,e,f&g), Grant-Marshall (2017)	Devic et al. (2014), Adeku (2015), Maquart et al. (2015), Murray and Newton (2015), Murray (2016), Popoff and Maquart, (2016a&b). Boadu (2017) (E. K. Boadu, personal communication, 16 October 2017), Devic et al. (2017), Maquart (2017) (P.O. Maquart, personal communication, 26 October 2017), Quilliam et al. (2017)	Enterra (2013, 2015, 2016a&b, 2017a,b,c&d), Marchant (2015), NZWC (2015), Leung (2016 & 2017), Nature (2016)

Box 2.2- Lessons from the case studies

The following are some lessons drawn from the four case studies analysed.

- (1) BSF technology has been implemented in a wide range of contexts, i.e. in countries with different income levels, in different climates, and at different scales. Indeed, BSF technology is becoming more and more attractive, in both developed and developing countries, to entrepreneurs, who want to take advantage of a potential huge market for animal feeds.
- (2) AgriProtein and Enterra Feed's case studies have demonstrated that implementing BSF technology at the large scale is technically feasible and economic viable, even in temperate climate, but requires large investments. Large-scale BSF facilities are characterized by high levels of automation and a highly controlled environment.
- (3) Medium-scale BSF facilities have the potential to improve organic waste management and create livelihood opportunities in low and middle-income countries, but their economic viability has not yet been proven. The semi-centralised organisation suggested by Diener et al. (2015a) could improve the economic performance of medium-scale BSF facilities, but such organisation has not yet been tested. Medium-scale facilities, as they cannot invest in the implementation of a highly controlled environment to rear BSF, have so far mainly been operated in tropical climate.
- (4) Despite differences in operational design from one facility to another, the overall organisation of the process is similar from one facility to another.
- (5) Pre-consumer food waste seems to be so far the waste stream favoured by BSF facilities, the exception being AgriProtein which is processing a wide range of organic materials. In this regard, large-scale facilities may be more able to treat mixed organic waste from multiple sources as they can invest in sorting and pre-processing equipment. On the other hand, treating a particular waste type from similar sources may be a better strategy for small or medium-scale facilities, which cannot invest in expensive pre-processing machinery.
- (6) At all scales, securing a sufficient supply of waste is one of the biggest challenges faced by BSF facilities. In addition, the economics of waste sourcing influences the overall economic profitability of the facility, especially in small and medium scale BSF facilities. In this regards, regulation and policy regarding organic waste management influences the economics of waste sourcing. For example, in places where valorising organic waste is compulsory, BSF facilities can get paid to take care of the waste. On the other hand, in the absence of regulation, BSF facilities may have to buy the waste from generators.
- (7) All the BSF facilities analysed sell the same kind of products, i.e., BSF larvae-based feed ingredients and fertilizer. However, larger-scale facilities propose higher grade products as they can invest in expensive refining equipment. To date, to the best of our knowledge, no commercial BSF facilities is post-processing the lipid content of the larvae into biodiesel or extracting the chitin from BSF prepupae.
- (8) Facilities in developing countries seem to face less legal problems to sell the larvae-based feed products, while in high-income countries, this constitutes an important issue that may hinder the economic viability of the facility. However, as more and more companies are getting their products approved, this may become a lesser problem in the future.

2.2.5 State of the research and need for further studies

To illustrate the status of the academic research on BSF technology, the focus of the studies reviewed, the main aspects and context they investigate, as well as the types of waste tested, and the date of publication were analysed. The main results from this analysis are presented in Table 2.14.

Table 2.14 - Overview of the literature published on BSF treatment

Focus of the study	Most of the studies on BSF technology focus on process engineering and the products of the process, while few studies deal with sustainability aspects, and even fewer with the implementation of BSF technology
Main aspect investigated	Studies published on BSF technology have so far deal extensively with the technical aspect of this treatment method, while the economic, environmental, legal, and social dimensions have been underexplored
Type of waste	Animal manure and food waste are the feedstock that have been the most extensively studied, followed by vegetal agro-industrial waste and human faeces
Income level	Most studies (~80%) do not look at a specific context. For studies that focus on a particular context, slightly more studies deal with high-income countries (12%) than with low- and middle-income countries (9%)
Climate	There is the same proportion (8%) of studies dealing with temperate climate as tropical climate
Date of publication	75% of the studies reviewed were published after 2005, and more than 50% after 2010

By reviewing the literature on organic waste treatment by BSF, several research gaps and needs for further research were identified. They are summarized in Table 2.15.

Table 2.15 - Research gaps pertaining to BSF technology

Theme	Research gaps
Feedstock	Optimal nutrient balance (e.g. C/N ratio), pH, and fibre content
Mating and oviposition	Mechanisms involved in the choice of an oviposition site by female flies, optimal space and fly density for mating
Waste treatment	Optimal thickness for the waste layer, oxygen requirement of the larvae, co-digestion of different waste types, role of microorganisms in the bioconversion process, nutrient flows through the process
Products	Optimal stage at which to harvest the biomass, safety of both products, properties of the waste residue, including nutrient composition, efficiency of the waste residue as a fertilizer, improvement of diet formulation of larvae meal, hygienisation and refining methods for both products.
Implementation of BSF technology	Optimal design and operating procedures for commercial BSF facilities, procedure for scaling up a BSF system
Economic aspect	Profitability of running a medium-scale BSF facility, quantification of the revenues from the sales of the different products, comparison of the economic performance for different feedstocks, applications, and contexts (climate, income level, scale, etc.), economic viability of the semi-decentralised organisation suggested by Diener et al. (2015a).
Environmental dimension	Quantification of the CO ₂ emissions associated with the BSF technology and comparison with other organic waste treatment methods, overall environmental performance of the BSF waste treatment process compared to other organic waste valorisation options, taking into account all the environmental benefits associated with the replacement of other raw materials for animal feeding, fertilizer or biodiesel production, comparison of different applications for the BSF larvae in terms of environmental impacts (e.g. animal feed vs biodiesel), comparison of the environmental performance of a BSF system for different substrates, specific inventory GHG data for BSF.
Social acceptance	Social acceptance of feeding animals with ingredients derived from BSF larvae reared on negatively perceived waste such as animal manure or human faeces, willingness of waste operators or farmers to adopt this technology.

Chapter 3: Technical Feasibility of Implementing a Low-tech Black Soldier Fly Bioconversion System for Faecal Sludge and Food Waste in Ghana

3.1 Background information for the technical feasibility study

Although BSF waste treatment constitutes a promising option for organic waste valorisation, the technical feasibility of implementing such technology for processing food waste and faecal sludge in Ghana must be established. A few small-scale experimental BSF valorisation units have been established in Ghana, mostly in Greater Accra, as part of research projects. However, to the best of the author's knowledge, they all focus on the bioconversion of fruit and vegetable waste. More generally, using BSF to valorise food waste, including fruit and vegetable waste, has been extensively studied (Alvarez, 2012; Barry, 2004; Nguyen et al., 2015; Parra Paz et al., 2015; Saragi and Bagastyo, 2015; Cheng and Lo, 2016; Leong et al., 2016). Indeed, reviewing the literature published on BSF technology (see Chapter 2:) revealed that food waste constitutes the second most examined waste type in the published literature, after animal manure. Compared to food waste, few studies have investigated the bioconversion of human waste by BSF (Lalander et al., 2013; Banks, 2014; Banks et al., 2014), and only one study was found on faecal sludge (Banks, 2014). Furthermore, when conducting a thorough literature search on BSF technology no published study was found on the co-digestion of food waste and faecal sludge by BSF. Therefore, this chapter focuses on examining the technical feasibility of implementing a low-tech BSF bioconversion system for food waste and faecal sludge in Ghana. More specifically, this part of the study aimed at establishing a small-scale pilot BSF valorisation unit including an artificial rearing system, and testing the system's performance in terms of both waste reduction and biomass production.

3.2 Methods and material for the technical feasibility study

To assess the technical feasibility of processing food waste and faecal sludge using a low-tech BSF valorisation system, a 10-week field work from December 2017 to February 2018 was conducted at the premises of the International Water Management Institute in Accra (see Figure 3.1). The field work was divided into two parts. The first part consisted of establishing a BSF colony through artificial rearing and evaluating rearing performance, while in the second part of the study, two sets of waste treatment trials were carried out to test the BSF bioconversion system performance in terms of both waste reduction and biomass production for different feedstock composition.

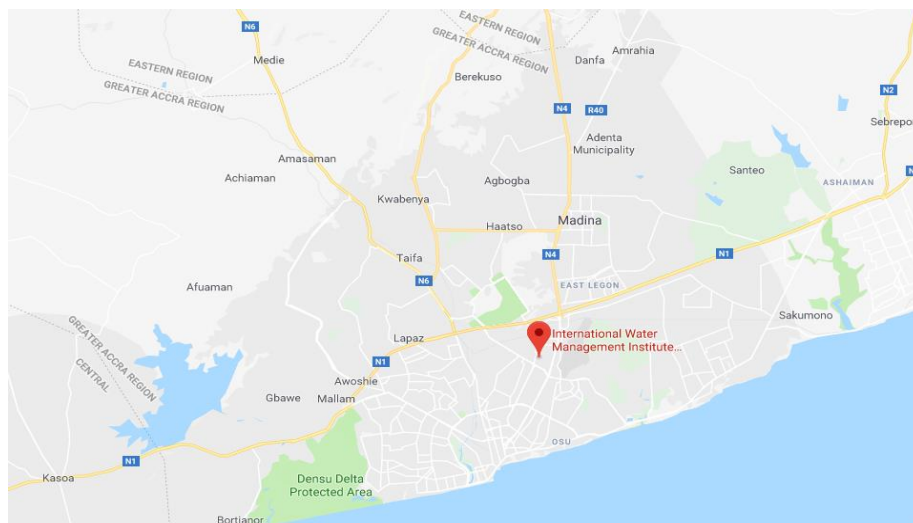


Figure 3.1 - Map of Greater Accra showing the location of the experimental site (Source: Google maps)

3.2.1 Acquisition of BSF

The colony was started using eggs obtained from an experimental artificial rearing system, which had itself been established with eggs from the wild indigenous BSF population and had been running for three years at the Biotechnology and Nuclear Agriculture Research Institute (BNARI) in Accra, Ghana.

3.2.2 Experimental setup

The experimental system was set up in a 16 m² shed (see Figure 3.2). The upper part of the structure, which initially consisted of metallic wire mesh, was fitted with mosquito net to reduce disturbance from other insects and animals, while allowing aeration. The experimental system was comprised of a waste treatment unit, where the waste treatment trials were conducted and a rearing unit, where BSF were bred (see Figure 3.3). The rearing unit was further divided into five subsystems, namely the mating cages, the hatchery, the larvae nursery, the prepupae collection system, and the pupation chamber.



Figure 3.2 - Shed in which the experimental system was set up



Figure 3.3 - Overview of the experimental system

- Rearing unit
 - Mating cages

To facilitate the recording of rearing data pertaining to the adult stage, three small cages (45 cm x 45 cm x 50 cm) were used. Indeed, Nakamura et al. (2016) showed that fertilized eggs could be obtained in a cage as small as 27 x 27 x 27 cm as long as the fly density was sufficient (e.g. ~ 5000 flies/m³). Cages were made of wooden frames and their sides and top were fitted with fine mesh, while a wooden panel was installed at the bottom (see Figure 3.4). On one of the side of the cages an opening was made in the mesh to allow the introduction of newly emerged flies and egg collection. To prevent flies from escaping the mesh was tied using a rubber band.



Figure 3.4 - Mating cages (45 cm x 45 cm x 50 cm netted cages)

Every morning, cages were placed outside to maximize exposure to sunlight and thus promote mating. They were then placed back inside the shed in the afternoon to avoid the flies' rapid dehydration and protect them from potential rain events. As the upper part of the shed's structure consisted of a mosquito net fitted on metallic wire mesh, the flies benefited from sunlight from approximately 6 am to 6 pm. To ensure that all the female flies laid their eggs in the same location and thus facilitate egg harvesting, oviposition media were provided. Their design was adapted from that proposed by Sheppard et al. (2002). Each oviposition medium consisted of five 10 cm x 2 cm strips of corrugated cardboard held together by two rubber bands (see Figure 3.5). The cardboard flutes provided suitable locations for the female flies to lay their egg packages (see Figure 3.6)



Figure 3.5 - Oviposition media made of corrugated cardboard



Figure 3.6 - Egg packages laid into cardboard flutes



Figure 3.7 – Oviposition medium placed on an attractant container

To attract the female flies to the oviposition media, 10 cm x 15 cm x 6 cm plastic containers, hereinafter referred to as attractant containers, filled with an attractant substrate consisting of a mixture of 100 g of fermented wheat bran mixed with water (70% moisture content), 50 g of the residue from an old nursery container, and 100 mL of water were used, based on the recommendations of Dortmans et al. (2017) and Mr. Ewusie (E.A. Ewusie, personal communication, 13 December 2017). Attractant containers were covered by a perforated lid fitted with a mesh to avoid flies laying eggs directly on the attractant substrate. One attractant container was placed in each cage with one oviposition medium placed above, on the mesh (see Figure 3.7).

To increase the lifespan of the flies, water was provided. To avoid flies drowning in the water, a petri dish filled with wet cotton was placed in each cage.

- Hatchery

Oviposition media were regularly collected from the mating cages, once egg clutches had been laid by BSF females, and replaced by new ones. Each collected oviposition medium was placed inside a 20 cm x 30 cm x 20 cm plastic container, referred hereinafter as hatching container (see Figure 3.8). Hatching containers were filled with a controlled diet made of 30% of wheat bran mixed with 70% of water, so that when eggs hatched, neonate larvae fell into the feed source and could immediately start feeding. Oviposition media were elevated using stones so that the eggs did not get wet (see Figure 3.9). In addition, a perforated lid fitted with mesh was placed above each hatching container to protect juvenile larvae from other insects while allowing air to flow. The hatching containers were then stored for about ten days to allow the eggs to hatch (3-4 days) and then neonate larvae to grow for a about 6 days in a relatively controlled environment with limited food competition.



Figure 3.8 - Hatching containers



Figure 3.9 – Oviposition media placed on stones above the feed source for neonate larvae

- Larvae nursery

About 6 days after hatching, the larvae were separated from the substrate through passive sieving (larvae fall naturally through the holes to escape light) using sieves with different mesh sizes (2 and 5 mm) (see Figure 3.10). A part of the juvenile larvae was then used to run the different waste treatment trials, while a fraction was kept in the rearing unit to maintain the colony. These latter larvae were transferred to 25 cm x 35 cm x 15 cm plastic containers, hereinafter referred to as nursery containers (see Figure 3.11), containing a control diet consisting of 30% of wheat bran mixed with 70% of water. About 3,500 larvae were placed into each nursery container (larval density of 4 larvae/cm²) and larvae were fed until they reach the prepupal stage with 100 mg of food/larva/day (wet weight) every three days based on a study by Diener et al. (2009b).



Figure 3.10 - Passive sieving system for juvenile larvae collection



Figure 3.11 - Nursery container (white) placed into a transfer container (orange)

- Prepupae collection system

Nursery containers were placed into larger containers (35 cm x 65 cm x 14 cm), hereinafter referred to as transfer containers, filled with coco peat, in order to collect migrating prepupae. Two wooden ramps were placed inside the nursery container, on each side, with an inclination of about 45° so that the prepupae in search for a dryer location could crawl out of the nursery container along the ramps and fall into the transfer container (see Figure 3.12).



Figure 3.12 – Prepupae crawling out the nursery container via the ramp and falling into the transfer container

- Pupation chamber

The harvested prepupae were then placed in 10 cm x 15 cm x 6 cm plastic boxes (100-500 prepupae per box), hereinafter referred to as pupation containers (see Figure 3.13), filled with compost mixed with water (~ 25% moisture content). Lids allowing air circulation fitted with a mesh was placed on top of the pupation containers. In addition to protecting the BSF pupae from parasitoid wasps, the mesh and the lid prevented newly emerged flies from escaping. The newly emerged flies were then released into the mating cages to mate and produce new eggs. The different containers used in the rearing unit were placed on a rack made of wood and metallic wire to minimize space requirement (see Figure 3.3).



Figure 3.13 - Pupation containers

- Waste treatment unit

Waste treatment trials were conducted in 10 cm x 15 cm x 6 cm plastic boxes, hereinafter referred to as treatment containers. Treatment containers were placed on a rack made of wood and metallic wire (see Figure 3.14). Like containers used in the rearing unit, treatment containers were covered with a perforated lid fitted with a mesh.



Figure 3.14 - Treatment containers

3.2.3 Establishment of a BSF colony and evaluation of rearing performance

To evaluate the performance of the rearing system established, it was run over two cycles and a number of performance indicators were monitored. The procedures followed to quantify these performance indicators are described below.

- Egg production

To monitor egg production by BSF in the mating cages, each oviposition medium was weighed before being placed into a mating cage. Once some females had laid eggs into an oviposition medium, it was weighed and the number of egg clutches laid was recorded. In addition, to assess the mean number of eggs laid by each BSF female, three egg clutches were randomly sampled during the course of the experiment and the number of eggs in each clutch was counted using a microscope. This operation was only performed three times to avoid the systematic manipulation of eggs, which are particularly sensitive. Finally, egg production was assessed by dividing respectively the egg weight, number of egg clutches, and number of eggs by the total number of female emerged (see below for estimation method)

- Hatching rate

The number of egg clutches and weight of eggs initially placed in each hatching container was recorded at the beginning of the incubation period. The number of eggs incubated was estimated based on the calculated mean number of eggs per clutch (see previous section). Determination of the hatching rate was based on the number of 6-day old larvae, as younger larvae were small to be accurately counted. Hence, about 6 days after having hatched, larvae from each hatching container were sieved from the diet residue and placed into a plastic bowl. The total weight of larvae collected per hatching container was measured. In addition, for each hatching container, two samples of 200 manually counted juvenile larvae were weighed to assess the mean weight of a juvenile larva, and thus estimate the total number of larvae collected per hatching container. Finally, the hatching rate was calculated using Equation (1).

$$\text{Hatching rate} = \frac{\text{Number of 6 – day – old larvae collected from the hatching container}}{\text{Number of eggs placed initially in the hatching container}} * 100 \quad (1)$$

- Larval development time and prepupae collection

For each nursery container, the initial number of juvenile larvae added was recorded. Then, from the day of apparition of the first prepupa, prepupae were collected, counted manually, and weighed for each nursery container every one or two days to analyse the prepupae appearance dynamics. Larval development time was defined as the day when half of the total prepupae collected had appeared.

- Pupation dynamics and time, adult emergence rate and sex ratio

The number of prepupae placed in each pupation container and the date when the pupation container was setup were recorded. Then, for each pupation container, the date when the first fly emerged was noted. From this date, the number of flies that emerged per pupation container and per day was recorded in order to analyse the pupation dynamics. Pupation time was defined as the time between the setting up of the pupation box and that when half of the pupae had emerged as flies. The adult emergence rate was defined as the proportion of pupae that emerged as fly and was calculated using Equation (2).

$$\text{Adult emergence rate} = \frac{\text{Number of emerged flies}}{\text{Number of pupae placed initially in the pupation container}} * 100 \quad (2)$$

An alternative method which was also used during the experimental period to assess the adult emergence rate, consisted of placing in each mating cage, a box containing 500 pupae. As the number of emerged flies could not be assessed accurately as they were alive, dead flies were collected at the end of the mating period and manually counted. Similarly, sex ratio, expressed as the proportion of females, was assessed by counting the number of collected dead flies that were females. Females were identified based on the presence of an ovipositor.

3.2.4 First waste treatment trial

- BSF larvae and waste

3,300 hand-counted 6-9 day-old larvae, obtained from the eggs provided by BNARI and previously reared in the nursery on a controlled diet, were used for this experiment. They were divided into 11 groups comprised of 300 larvae each. Ten groups of larvae were fed with five different diets (two groups per diet) consisting of either food waste, faecal sludge, or a mixture of these wastes in varying mass ratios. The last group of larvae was fed with a control diet made of wheat bran (30%) and water (70%). The composition of the waste-based diets is presented in Table 3.1.

Table 3.1 - Composition of the 5 waste-based diets used in the first experiment

Diet	Food waste (% wet weight)	Rehydrated dewatered faecal sludge (% wet weight)
FW100	100	0
FW75	75	25
FW50	50	50
FW25	25	75
FW0	0	100

Both food waste and faecal sludge were obtained from *FortifierTM* plant, a composting plant located in Tema Metropolis and operated by Jekora Ventures Ltd. Faecal sludge from households and public toilets (pit latrines and septic tanks) was collected for the experiment after having gone through a dewatering process for about two weeks in drying sand beds to reduce its pathogenic content and makes it easier to handle (see Figure 3.15), while food waste was obtained on the day of its collection by Jekora Ventures Ltd from households and institutions participating in its waste segregation program. A visual inspection of the food waste indicated that it was mainly comprised of fruit and vegetable waste, as well as meat bones (see Figure 3.16Figure 3.16).



Figure 3.15 - Dewatered faecal sludge used in the first experiment



Figure 3.16 - Food waste used in the first experiment

The moisture content of the food waste, which was about 70%, was in the suitable range for BSF processing. Therefore, no water addition was required to prepare the diet made of 100% of food waste (FW100). On the other hand, since the dewatered faecal sludge had a moisture content of only 30%, water was added to all the other diets containing faecal sludge, in order to obtain a moisture content similar to that of FW100 diet. The quantity of water to add to obtain the targeted moisture content was determined using Equation (3).

$$\text{Mass}_{\text{water}} = \frac{\text{Mass}_{\text{diet}} * (\text{MC}_{\text{diet}} - \text{MC}_{\text{waste}})}{100 - \text{MC}_{\text{waste}}} \quad (3)$$

where MC_{diet} and MC_{waste} refer respectively to the moisture content targeted for the diet (about 70%) and the moisture content of the waste mixture without water (in %). On the other hand, $\text{Mass}_{\text{water}}$ and $\text{Mass}_{\text{diet}}$ are respectively the mass of water to add to the waste mixture, and the total mass of the diet to prepare.

As regular supply of food waste and faecal sludge was not guaranteed during the experimental period, diets for the whole feeding period were prepared in advance and stored at about 6°C in a fridge before use. The different feedstocks were thoroughly mixed manually prior to feeding it to the larvae to make it as homogeneous as possible. To determine the moisture content of the different feedstocks prepared, samples of fresh material were collected for each feedstock and weighed. The samples were then dried at IWMI's lab by placing them in an incubator at 100°C for 24 hours. The weight of the dry material was then recorded, and the moisture content was obtained using Equation (4).

$$\text{Moisture content [\%]} = \frac{\text{wet weight} - \text{dry weight}}{\text{wet weight}} * 100 \quad (4)$$

The moisture contents of the different diets used in the experiment are presented in Table 3.2. They do not differ significantly and are all within the suitable range for BSF processing, which is 60 - 90% (Cammack and Tomberlin, 2017; Cheng et al., 2017; Dortmans and al., 2017; Lohri et al., 2017).

Table 3.2 - Moisture content of the 5 diets used in first experiment

Diet	Moisture content (%)
FW100	68
FW75	68
FW50	67
FW25	69
FWo	70
Control diet	71

- **Experimental operation**

Each group of 300 larvae was placed into a 150 cm² plastic box (larval density of 2 larvae/cm²) covered by a perforated lid fitted with a mesh to avoid oviposition by other flies and prevent larvae from escaping. Larvae in each group were fed every 3 days at a feeding rate of 100 mg/larva/day (wet weight). These operational parameters were chosen based on studies by Diener et al. (2009b) and Parra Paz et al. (2015). The larvae in each group were fed until half of the larvae had turned into prepupae, which was identified by a change of colour of the larvae from white to dark brown. This threshold was chosen because it had been used in several other researches (e.g. Diener et al. (2009b) and Banks et al. (2014)). The experiment was duplicated for each waste-based diet. In addition, a control with the same feedstock composition, same amount of material added but no larva was associated to each feedstock to assess whether waste reduction was due to the larvae. Finally, an additional container where 300 larvae were fed on wheat bran mixed with water was also used as a control. Containers were placed randomly on a shelf within the experimental system.

- **Sampling and analysis**

For each group, the larvae were hand-counted and weighed at the beginning of the experiment. Then, every two days, ten larvae from each group were randomly sampled, washed with distilled water, weighed, and placed back in the feeding container. For the treatments characterized by high larval mortality, when it was not possible to identify ten living larvae, fewer larvae were sampled. When prepupae started appearing, they were removed from the treatment containers, counted, weighed, and taken to the pupation chamber in the rearing unit to pupate into flies. At the end of the feeding period, all the remaining larvae and prepupae were removed from the waste residue manually using tweezers and counted. The larvae and prepupae collected were weighed separately to measure their respective mass. Samples of larvae and prepupae were taken for each treatment and dried at 60°C for 24 hours for dry weight determination. As for the waste residue, it was weighed and a sample was dried at 100°C for 24 hours for dry weight assessment. In the treatments where larvae did not experience any growth, waste stopped being added at the end of the feeding period of the last treatment where larvae succeeded in reaching the prepupal stage. For these former treatments, larvae, which were still alive, were collected, counted, and weighed. When it was possible, one sample of larvae was taken for dry weight assessment. As for the waste residue, it was weighed and a sample was dried.

- Calculation and statistical analysis

To take into account both waste treatment and animal feed production perspectives, the performance of the BSF bioconversion system was evaluated for each feedstock in terms of the following parameters: waste reduction rate, bioconversion rate, feed conversion ratio, average larval and prepupal weight, larval development time, and larval survival rate. These parameters are defined as follows:

The waste reduction rate was estimated using Equation (5).

$$\text{Waste reduction rate} = \frac{W_1 - W_2}{W_1} * 100 \quad (5)$$

Where W_1 is the initial weight of the waste added to the treatment container and W_2 is the weight of the waste residue after BSF bioconversion, measured when 50% of the larvae have turned into prepupae. High waste reduction rate indicates good reduction efficiency. Both wet and dry waste reduction rates were calculated to enable comparison with the values reported in the literature.

The bioconversion rate was calculated using Equation (6).

$$\text{Bioconversion rate} = \frac{\text{final weight of the larval biomass}}{\text{Initial weight of waste added}} * 100 \quad (6)$$

Where the larval biomass includes both larvae and prepupae harvested from the waste residue when 50% of the larvae have turned into prepupae. A high bioconversion rate indicates a good bioconversion efficiency. Like the waste reduction rate, both the wet and dry values of the bioconversion rate were calculated.

The feed conversion ratio (FCR) was estimated using Equation (7).

$$\text{FCR} = \frac{\text{total weight of feed ingested by the larval biomass}}{\text{weight gained by the larval biomass}} \quad (7)$$

Where the weight gained was estimated by subtracting the initial weight of the total larval biomass added to the feeding container at the beginning of the experiment to the total weight of the larvae and prepupae collected at the end of the feeding period (when 50% of the larvae have turned into prepupae). Similarly, the total weight of the feed ingested by the larvae was calculated by subtracting the final weight of the waste residue at the end of the feeding period to the initial weight of the waste added to the treatment container. A low feed conversion ratio indicates a good feed conversion efficiency. Both wet and dry FCR were estimated. The larval development time was defined by the time required for 50% of the larvae to turn into prepupae, while the survival rate was considered to be the proportion of juvenile larvae still alive at the end of the feeding period.

The results of the experiments were analysed statistically by conducting a one-way analysis of variance (ANOVA) followed by a Tukey HSD (honestly significant difference) test when more than two treatments were considered and a t-test when only two treatments were examined. A P value < 0.05 was considered to indicate a significant difference between the values compared.

3.2.5 Second waste treatment trial

- BSF larvae and waste

4,800 6-7 day-old larvae obtained by incubating eggs from the BSF colony established as part of this study (see Section 3.2.2) were used in this experiment. They were divided into 16 groups (8 treatments performed in duplicates) comprised each of 300 larvae. As it was hypothesized that poor performance recorded in the first experiment for the faecal sludge-based treatments was due to the use of highly dewatered faecal sludge whose structure after rehydration was not suitable for larval feeding, the waste-based treatments performed in the first experiment were replicated using, instead of highly dewatered faecal sludge, faecal sludge that had only be dewatered for three days to reach a moisture content suitable for larval feeding (raw faecal sludge being too liquid). Since treatments containing 100% of food waste performed well in the first experiment, food waste was used as a control diet in the present experiment. In addition to using slightly dewatered faecal sludge instead of highly dewatered faecal sludge, the influence of mixing the faecal sludge with a structuring material, such a crushed charcoal, on the bioconversion performance of faecal sludge by BSF was investigated. The eight treatments performed in this experiment are described in Table 3.3.

Table 3.3 - Description of the 8 treatments performed as part of the 2nd waste treatment trial

Treatment	Composition (wet weight)
FW100	100% food waste
FW75	75% food waste and 25% slightly dewatered faecal sludge
FW50	50% food waste and 50% slightly dewatered faecal sludge
FW25	25% food waste and 75% slightly dewatered faecal sludge
SDFS	100% slightly dewatered faecal sludge
HDFS	100% rehydrated highly dewatered faecal sludge
SDFS + CC	90% slightly dewatered faecal sludge and 10% of crushed charcoal (particle size < 5 mm)
HDFS+ CC	90% rehydrated highly dewatered faecal sludge and 10% of crushed charcoal (particle size < 5 mm)

As in the first waste treatment, food waste, and both slightly and highly dewatered faecal sludge were obtained from *Fortifier™* composting plant. Similar procedures as those described in Section 3.2.4 were followed for feedstocks' preparation and storage. The moisture content of the 8 diets prepared are presented in Table 3.4.

Table 3.4 - Moisture content of the 8 diets used in the 2nd experiment

Treatment	Mean moisture content (%)
FW100	73 ± 3.6
FW75	75 ± 4.5
FW50	72 ± 0.3
FW25	73 ± 10.1
SDFS	70 ± 0.3
HDFS	65 ± 2.2
SDFS + CC²	65 ± 0.7
HDFS+ CC³	57 ± 2.2

Values are reported as mean ± standard deviation (n = 2)

² This value includes the moisture content of charcoal. Therefore, the moisture content of the consumable material (i.e. material without charcoal) is actually higher.

³ Idem

- Experimental operation

Each group of larvae was placed into a 150 cm² plastic box covered by a perforated lid fitted with a mesh. The same operational parameters values as the first experiment were adopted (i.e. larval density: 2 larvae/cm²; feeding rate: 100 mg/larva/day⁴; feeding regime: incremental, every three days; end of the feeding period: 50% of the larvae have turned into prepupae).

- Sampling, calculation, and statistical analysis

The same procedure as in the first experiment was followed. The bioconversion performance associated with each treatment was evaluated in terms of the same parameters as in the first experiment, i.e. waste reduction rate, bioconversion rate, feed conversion ratio, average larval and prepupal weight, larval development time, and larval survival rate (see Section 3.2.4 for definitions and Equations (5), (6), and (7) for formulas). In addition, the results of the experiments were analysed statistically using the same method as in the first experiment.

⁴ For the diets containing crushed charcoal (SDFS + CC and HDFS + CC), the feeding rate was adjusted so that the larvae were fed the same amount of consumable material as that in the other treatments.

3.3 Results and discussion for the technical feasibility study

3.3.1 Rearing performance

Table 3.5 presents the mean, minimum, maximum, and standard deviation values for various rearing performance indicators, recorded during the course of the experiment. These experimental values are compared to values reported in the literature in Table 3.6.

Table 3.5 - Experimental values recorded for selected rearing performance indicators

Indicator	Unit	Mean	Minimum	Maximum	Standard deviation	n
Egg production (# eggs)	eggs/female	32	15	45	15	3
Egg production (# clutches)	clutches/female	0.07	0.03	0.10	0.03	3
Hatching rate	%	59	39	80	29	2
Larval development time	days	16	14	18	1.8	4
Prepupal weight	g (wet)	0.08	0.07	0.09	0.01	4
Adult emergence rate	%	77	31	99	25	6
Pupation time	days	9.3	9	10	0.6	3
Sex ratio	% of females	28	20	35	7	3

n: number of experimental values on which the calculations are based

Egg production was assessed in terms of the weight and number of eggs and clutches laid. However, the weight of eggs laid is not presented in Table 3.5, as its estimation was judged unreliable. Indeed, it was affected by the variation of the oviposition media's weight due to moisture absorbed by the cardboard, which could not be estimated accurately. Similarly, experimental values reported for the number of eggs per female constitute rough estimation as they are based on only three measurements of the number of eggs per clutch. Yet, egg clutches' size is highly variable (Tomberlin et al., 2002; Nakamura et al., 2016). By contrast, the number of egg clutches laid could be measured relatively easily and thus the value reported for the number of clutches per female is probably the most accurate measure of the egg production. Experimental values reported for the egg production, either in terms of the number of eggs or clutches per female are very low compared to those reported in the literature (see Table 3.5 and Table 3.6).

A first parameter that probably contributed to the absolute low egg production recorded is the sex ratio which was severely unbalanced in favour of males (only 28% of females on average). Only one study reporting an unbalanced sex ratio, by Caruso et al. (2013), was found. The authors observed a mean sex ratio of 36% of females in a BSF rearing unit located in Indonesia. Based on various values reported in this study and the average weight of an egg (28 µg) reported by Booth and Sheppard (1984), it was calculated that the mean egg production in this facility was 53 eggs/female. This value is still higher than that recorded in this present study but closer in order of magnitude compared to values reported by Nakamura et al. (2016) and Dortmans et al. (2017) (see Table 3.6). No study was found on the parameters influencing sex determination for the BSF. On the contrary, Tomberlin et al. (2002) who measured the sex ratio of BSF fed with three different artificial diets (i.e. non-waste diets) and BSF from the wild population did not report any significant difference between diets and origins (wild vs captivity). Yet, despite the unbalanced sex ratio, given the number of emerged females, a higher egg production was expected. Indeed only 7% of the females that emerged laid eggs. Therefore, the unbalanced sex ratio alone does not account for the low egg production.

Table 3.6 - Values reported in the literature for the same rearing performance indicators

Indicator	Unit	Mean	Min	Max	Stdev	# values	References
Egg production (# eggs)	eggs/female	293	240	350	55	3	Nakamura et al. (2016), Dortmans et al. (2017)
Egg production (# clutches)	clutches/female	0.43	0.43	0.43	NA	1	Nakamura et al. (2016)
Hatching rate	%	49	5	86	32	9	Holmes et al. (2012), Caruso et al. (2013), Dortmans et al. (2017)
Larval development time	days	13.3	12.5	14.1	0.8	3	Tomberlin et al. (2002)
Prepupal weight	g (wet)	0.11	0.10	0.11	0.00	4	Tomberlin et al. (2002), Cammack and Tomberlin (2017)
Adult emergence rate	%	63	16	93	28	15	Tomberlin et al. (2002), Holmes et al. (2012), Caruso et al. (2013), Lin (2016), Dortmans et al. (2017)
Pupation time	days	10.3	8.0	14.0	2.0	6	Sheppard et al. (2002), Holmes et al. (2012), Caruso et al. (2013)
Sex ratio	% of females	51	36	61	7	11	Tomberlin et al. (2002), Caruso et al. (2013) and Lin (2016)

By reviewing the literature on BSF, three environmental parameters were found to significantly influence mating and oviposition of the BSF, namely temperature, light, and humidity. Temperature and humidity could not be recorded during the course of the experiments but data from a nearby weather station recorded temperatures ranging from 24 to 33°C and a relative humidity between 80 and 90% during the mating and oviposition period (weatheronline.co.uk, 2018). Booth and Sheppard (1984) observed that 99.6% of oviposition occur between 27.5 and 37.5°C, while Tomberlin and Sheppard (2002) reported that 80% of eggs are laid when humidity exceeds 60%. Therefore, temperature and humidity conditions during the experimental period were conducive for egg production. Similarly, light requirement for mating was met as mating cages were placed outside early in the morning to be exposed to direct sunlight. Indeed, Tomberlin and Sheppard (2002) and Zhang et al. (2010) reported that mating usually occurs in the morning and is promoted by sunlight. Therefore, temperature, humidity, and light conditions are unlikely to account for the poor egg production. However, a potential explanation is the weight of the prepupae collected from the nursery container which is significantly lower compared to values reported in the literature for larvae fed on artificial diets. Yet, the BSF relies solely on the fat accumulated as larva to sustain its biological activity in the adult stage (Diener, 2010&2017; Tomberlin and Sheppard, 2002). Therefore, if not enough fat is stored during the larval stage, the adult fly will die rapidly without having time to reproduce. As suggested by the low prepupal weight, this may have been one of the reasons for the low egg production. Therefore, to increase egg production, a more nutritional diet could be fed to the larvae in the nursery for example by mixing wheat bran with corn meal and alfalfa meal, as suggested by Sheppard et al. (2002), or using poultry feed (Diener et al., 2009b; Dortmans et al., 2017).

On the other hand, hatching rates measured experimentally are on average higher than those reported in the literature. However, they were calculated based on the mean number of eggs per clutch, which was estimated based on a limited number of observations. Similarly, on average the adult emergence rate was higher than those reported in the literature, but it was also characterized by a high degree of variability. In addition, the mean larval development time recorded experimentally is longer than that reported by Tomberlin et al. (2002), probably due to the lower nutritional value of the diet used in this study. Figure 3.17 shows the mean cumulative percentage of prepupae collected over time. The first prepupae started appearing after about 10 days spent in the nursery. Then, prepupae appeared at a relatively steady rate, except for the first days. However, after 25 days, very few prepupae were collected.

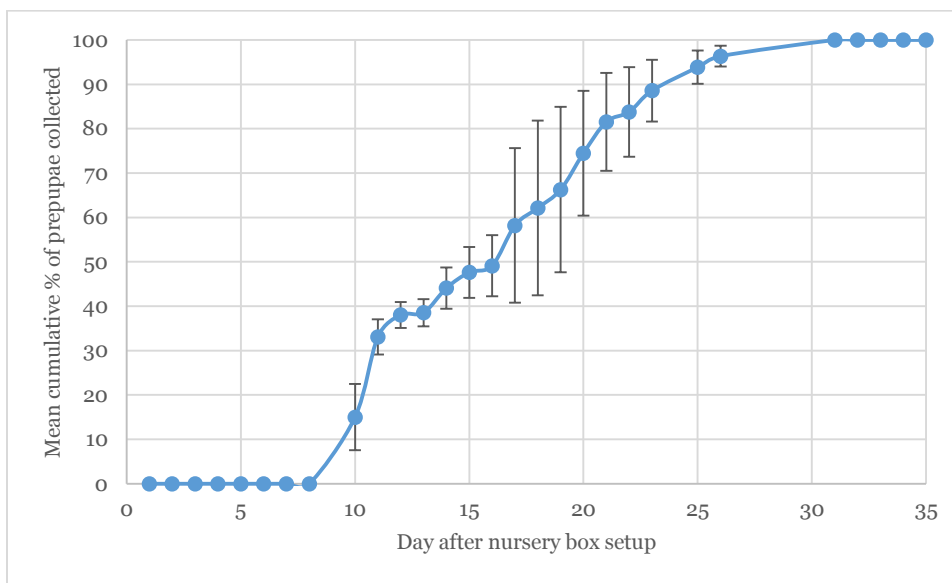


Figure 3.17 - Prepupae collection dynamics
Bars indicate standard deviations (n = 4)

Finally, the pupation time measured experimentally compares positively with values reported in the literature. Figure 3.18 displays the mean number of flies emerging per day over time. The first flies started emerging after 7 days of incubation. Then fly emergence follows a bell-shaped curve, a trend also observed by Caruso et al. (2013), Lin (2016), and Dortmans et al. (2017). Finally, after 13 days, flies stopped emerging.

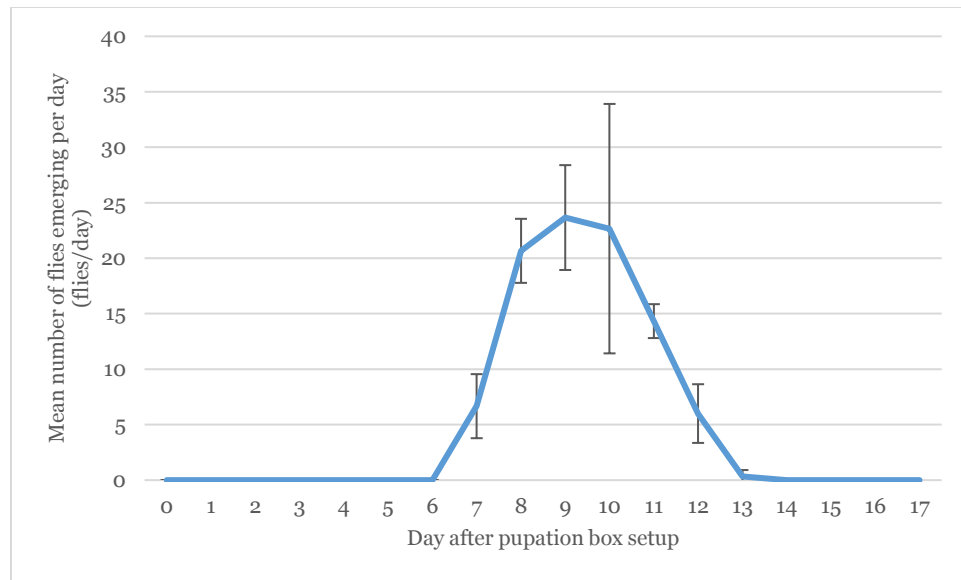


Figure 3.18 - Pupation and fly emergence dynamics
Bars indicate standard deviations (n = 3)

Overall, except for egg production and sex ratio, rearing performance values measured in this study were comparable to those reported in the literature, indicating that artificially breeding BSF in Ghana using a low-tech rearing system is technically feasible. However, optimization efforts should emphasize increasing egg production, as achieving a reliable supply of juvenile larvae and thus of eggs is crucial to be able to scale up such system. In this regard, the effect of changing the nursery diet could be investigated. Moreover, to increase the reliability of the performance results, they should be measured based on more observations recorded over a larger number of cycles.

3.3.2 Fist waste treatment trial

- Larval survival rate, weight gain and development time

Figure 3.19 displays the weight gained over time by BSF larvae fed with the six different diets described in Section 3.2.4, while Table 3.7 shows larval survival rates, development times, as well as final larval and prepupal weights (measured on both wet and dry basis) for the different treatments.

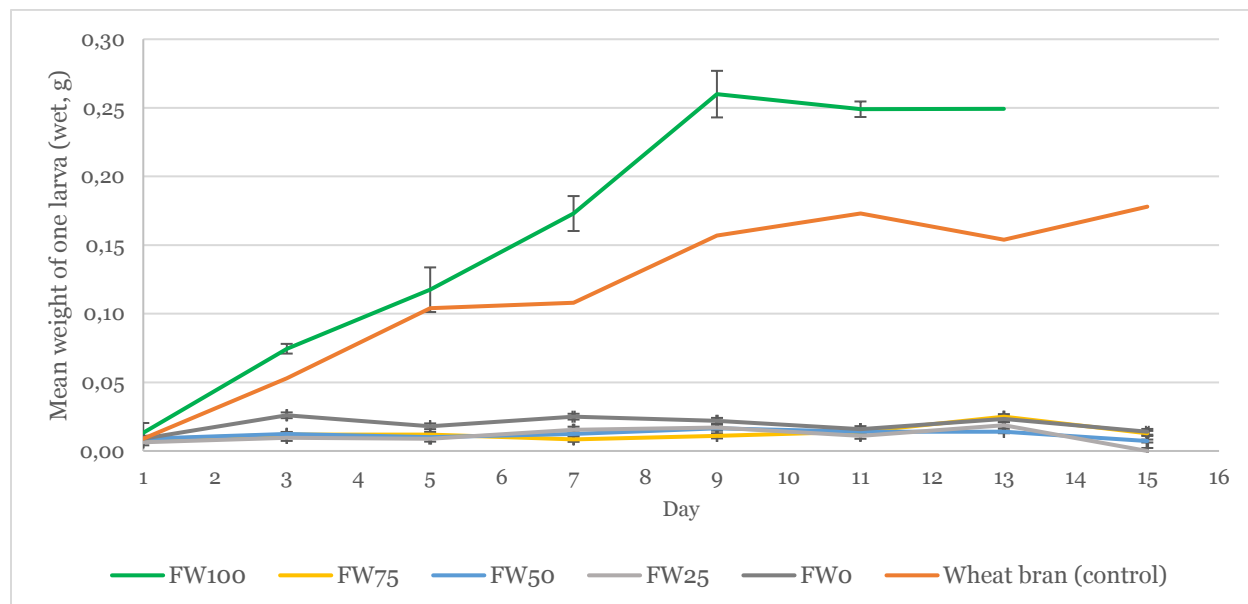


Figure 3.19 - Weight gained over time by BSF larvae fed with six different diets consisting of food waste (FW100), faecal sludge (FW0), mixtures of food waste and faecal sludge in mass ratios 3:1 (FW75), 1:1 (FW50), 1:3 (FW25), and wheat bran mixed with water (control). Bars indicate standard deviations (n = 2).

Table 3.7 - Survival rates, development times, larval and prepupal weights of BSF fed with different diets

Diet	Larval survival rate (%)	Larval development time (days)	Larval weight at the end of the feeding period (g)		Prepupal weight (g)	
			Wet basis	Dry basis	Wet basis	Dry basis
FW100	95.7 ± 3.30 ^a	12.5 ± 0.71 ^a	0.25 ± 0.00 ^a	0.09 ± 0.00 ^a	0.21 ± 0.01 ^a	0.08 ± 0.00 ^a
FW75	7.7 ± 0.47 ^b	No development	0.01 ± 0.00 ^b	0.00 ± 0.00 ^b	No prepupa	NA
FW50	4.0 ± 3.77 ^b	No development	0.01 ± 0.01 ^b	0.00 ± 0.00 ^b	No prepupa	NA
FW25	0.7 ± 0.47 ^b	No development	0.00 ± 0.00 ^b	0.00 ± 0.00 ^b	No prepupa	NA
FW0	4.2 ± 5.42 ^b	No development	0.01 ± 0.02 ^b	0.00 ± 0.00 ^b	No prepupa	NA
Control diet	96.0 ^a	15.0 ^a	0.18 ^c	0.05 ^c	0.13 ^b	0.04 ^b

Values are reported as mean ± standard deviation (n = 2). Mean values followed by the same letter in the same column do not differ significantly (P > 0.05).

FW100 (100% food waste) resulted in the highest larval and prepupal weights (mean dry prepupal weight: 0.08 g) in the shortest time (mean development time: 12.5 days). The control diet (70% water and 30% wheat bran) constitutes the second best treatment in terms of weight gain and development time. Larvae fed on the control diet developed in 15 days into prepupae exhibiting a dry weight of 0.04 g. As shown by Table 3.7, larval development times recorded for FW100 and the control diet do not differ significantly. By contrast, larval and prepupal weights for FW100 and the control diets are significantly different. Figure 3.20 illustrates the significantly higher prepupal yield obtained with FW100 than with the control diet.



Figure 3.20 - Samples of 10 prepupae from the control diet (left) and FW100 (right)

Regarding larval survival rate, there is no significant difference between FW100 and the control diet, which both exhibit a larval survival rate of about 96%. Unlike FW100 and the control diet, characterized by high larval survival rates, all the treatments containing faecal sludge (i.e. FW0, FW25, FW50, FW75), even in small amount (25%), exhibited a high larval mortality. In these latter treatments, after 15 days of feeding, very few larvae had survived (1 to 8 %, depending on the proportion of faecal sludge). Therefore, survival rates for the faecal sludge-based diets are significantly different from those obtained for FW100 and the control diet. However, survival rate does not vary significantly across the different faecal sludge-based diets. In addition, the larvae that had survived did not exhibit any weight gain, since the larval weight recorded at the end of the experimental period (≤ 0.1 g, wet basis) was similar to that of the larvae initially added to the treatments (0.01 g, wet basis). As a result, no larvae from the faecal sludge-based treatments reached the prepupal stage.

In Table 3.8, experimental values obtained in the present study are compared to those reported in the literature for feedstocks similar to those used in this experiment. Regarding the treatment consisting of only food waste (FW100), the larval survival rate recorded (96%) in this study is higher than those reported by Nguyen et al. (2013) for BSF larvae fed on kitchen waste (47%) and fruit and vegetable waste (77%). The BSF larvae in FW100 also developed faster in the present study (12.5 days) than in other studies, which report larval development ranging from 19 to 29 days. Similarly, the wet larval weight measured in this experiment is up to twice higher than those reported in the literature. By contrast, similar prepupal weight data were obtained in this study for FW100 than the highest values reported by Diener et al. (2011) for municipal organic waste, which probably consisted mainly of food waste. Therefore, overall, values pertaining to larval survival and development obtained in this study compare positively with those reported in the literature for similar feedstocks.

Table 3.8 - Comparison of the values pertaining to larval survival and development obtained in this study with those reported in the literature

Feedstock	Larval survival rate (%)	Larval development time (days)	Mature larval weight (g)	Prepupal weight (g)		Reference
			Wet basis	Wet basis	Dry basis	
Food waste (FW100)	96	12.5	0.25	0.21	0.08	This study
Faecal sludge (FWo)	4	No growth recorded	0.01	NA	NA	This study
Mixture of FW and FS (FW75,50&25)	8 - 1	No growth recorded	≤ 0.01	NA	NA	This study
Kitchen waste	47	24	0.17	-	-	Nguyen et al. (2013)
Restaurant waste	-	19	0.15	-	-	Sprangers et al. (2017)
Fruit and vegetable waste	77	29	0.12	-	-	Nguyen et al. (2013)
Vegetable waste	-	16	0.14	-	-	Sprangers et al. (2017)
Municipal organic waste	-	-	-	0.14 - 0.22	0.06 - 0.09	Diener et al. (2011)
Fresh human faeces	-	8-12	-	0.19 - 0.32	-	Banks et al. (2014)
FS from pit latrine	-	-	-	-	0.03- 0.07	Banks (2014)

Unlike food waste, experimental values recorded for faecal sludge-based diets compare poorly with those reported in the literature for similar feedstocks (fresh human faeces and faecal sludge from pit latrines). While treatments containing faecal sludge were characterized by low survival rates and no apparent larval growth in the present study, other studies demonstrated that fresh human faeces and pit latrine faecal sludge are suitable for BSF bioconversion (Banks, 2014; Banks et al., 2014). Indeed, these feedstocks are associated with performance indicators pertaining to larval development, which, although generally slightly lower, remain comparable to values reported for food waste. No study regarding the co-digestion of food waste and faecal sludge was found.

A factor that could explain the differences between values pertaining to larval survival development obtained in this study for faecal sludge-based diets and those reported in the literature for similar feedstocks is that the faecal sludge used in this experiment had gone a desludging process, consisting of adding water to the faecal sludge and then dewatering the mixture to reduce its pathogenic content and make it easier to handle, while raw human waste was used in the other studies. Therefore, it is hypothesized that drying and then rehydrating the faecal sludge to obtain a moisture level suitable for BSF processing altered the structure of the material and made it unsuitable for larval feeding, even when mixed with food waste. This is supported by the observation that at the beginning of the feeding period, larvae in the faecal sludge-based treatments were unable to burry completely into and move through the feedstock. As a result, most of the larvae tried to crawl away from the feed source or got stuck with their body half buried into the substrate. A thorough literature review revealed that feedstock structure is a parameter rarely discussed in the literature. However, a few authors highlighted its importance in the bioconversion process by BSF. In particular, Barry (2004) and Perednia (2016) pointed out that the feedstock should have enough structure to allow the larvae to move through the material, consume it, and get an adequate supply of oxygen. Therefore, the high larval mortality and absence of larval growth observed in the faecal sludge-based diets may have been caused by starvation and asphyxiation of the larvae due to their inability to move through the substrate, itself a consequence of a lack of structure of the feedstock. In this regard, Perednia (2016) recommended adding matrix materials, such as pine shavings and crushed charcoal, to improve the ability of BSF larvae to burrow and move through the waste pile.

Another potential cause for the high mortality rate observed in the treatments containing faecal sludge is the presence of non-excreta additives, such as cleaning or odour control chemicals, in the faecal sludge. Banks (2014) studied the impact on BSF larvae mortality of different cleaning chemicals commonly used by households in South-Africa. The study revealed that some cleaning chemicals had a significant influence on BSF larvae mortality. However, Banks (2014) pointed out that obtaining mortality rates greater than natural levels would require using these chemicals in concentrations that are far higher than manufacturer's guidelines and household reported use. Even if cleaning chemicals used by Ghanaian households might be different from those used in South-Africa, the hypothesis that high mortality is caused by cleaning chemicals in faecal sludge is unlikely as otherwise decreasing the proportion of faecal sludge would have resulted in reduced mortality, which is not the case, as shown in Table 3.7.

- Waste reduction rate, bioconversion rate, and feed conversion ratio

Table 3.9 presents the waste reduction rate, bioconversion rate, and feed conversion ratio, measured on both wet and dry basis, for each diet, in the presence of BSF larvae.

Table 3.9 - Waste reduction rates, bioconversion rates, and feed conversion ratios for the six different diets

Diet	Waste reduction rate (%)		Bioconversion rate (%)		Feed conversion ratio	
	Wet basis	Dry basis	Wet basis	Dry basis	Wet basis	Dry basis
FW100	65.41 ± 4.08 ^a	66.70 ± 1.05 ^a	17.98 ± 0.57 ^a	20.73 ± 1.07 ^a	3.89 ± 0.51 ^a	3.23 ± 0.41 ^a
FW75	42.87 ± 0.43 ^b	21.98 ± 2.59 ^b	0.07 ± 0.02 ^b	0.05 ± 0.02 ^b	No weight gain	No weight gain
FW50	35.01 ± 0.60 ^c	12.40 ± 8.74 ^{bc}	0.03 ± 0.05 ^b	0.00 ± 0.00 ^b	No weight gain	No weight gain
FW25	31.75 ± 2.15 ^c	0.99 ± 3.14 ^c	0.00 ± 0.00 ^b	0.00 ± 0.00 ^b	No weight gain	No weight gain
FW0	29.42 ± 0.18 ^c	-0.82 ± 2.19 ^c	0.07 ± 0.11 ^b	0.04 ± 0.05 ^b	No weight gain	No weight gain
Control diet	67.58 ^a	57.85 ^a	9.65 ^c	10.02 ^c	3.68 ^a	3.60 ^a

Values are reported as mean ± standard deviation (n = 2). Mean values followed by the same letter in the same column do not differ significantly (P > 0.05).

Regarding waste reduction rates, for the treatments with BSF larvae, no significant difference was recorded between FW100 and the control diet. Similarly, the waste reduction rate does not vary significantly across faecal sludge-based diets. By contrast, waste reduction rates obtained for FW100 and the control diets are significantly higher than those recorded for the diets containing faecal sludge. On wet basis, the control diet exhibits the highest waste reduction rate (68%), and FW100 the second highest (65%). In contrast, when waste reduction rate is measured on dry basis, FW100 is characterized by a higher waste reduction rate (67%) than the control diet (58%). According to Banks (2014), dry waste reduction rates are more accurate than wet waste reduction rates since they exclude the varying water content of the initial diet and waste residue. However, errors occurred when estimating dry waste reduction rates as, for some of the replicates, greater values were obtained when measuring the weight of the dry residue than the dry weight of matter added. Such result indicates a net mass gain, which is impossible as no other solid was added. Similar errors were reported by Banks (2014) but the source was not identified. Since these errors concern only 13% of the data, dry waste reduction rates are still presented in Table 3.9, with erroneous data depicted in red. However, wet waste reduction data are used for comparison purpose. For the waste-based diets, i.e. FW100, FW75, FW50, FW25, and FW0, the higher the proportion of food waste, the greater the waste reduction rate, a trend observed on both wet and dry basis, as well as with and without BSF, as shown in Figure 3.21. Indeed, whether BSF larvae are present or absent, dehydration and microbial activity contribute to waste reduction. In this regard, the greater waste reduction rate observed in treatments containing higher proportions of food waste, both with and without BSF, is likely partly due to differences in microbial communities in the food waste and faecal sludge. In addition, comparing wet waste reduction rates with and without BSF larvae reveals that significantly higher waste reduction is achieved in the presence of BSF larvae.

This likely explains why waste reduction rate recorded for FW100 and the control diet are significantly higher than the other diets, since larval activity was much higher in the former treatments than the latter, as shown by larval survival and growth data. Moreover, the significant contribution of BSF larvae in waste reduction also explains why for FW100, characterized by high larval activity, the difference in waste reduction rate with BSF and without BSF larvae (27%) is much higher than for the faecal-sludge based treatments (only about 10%), where low larval activity was recorded.

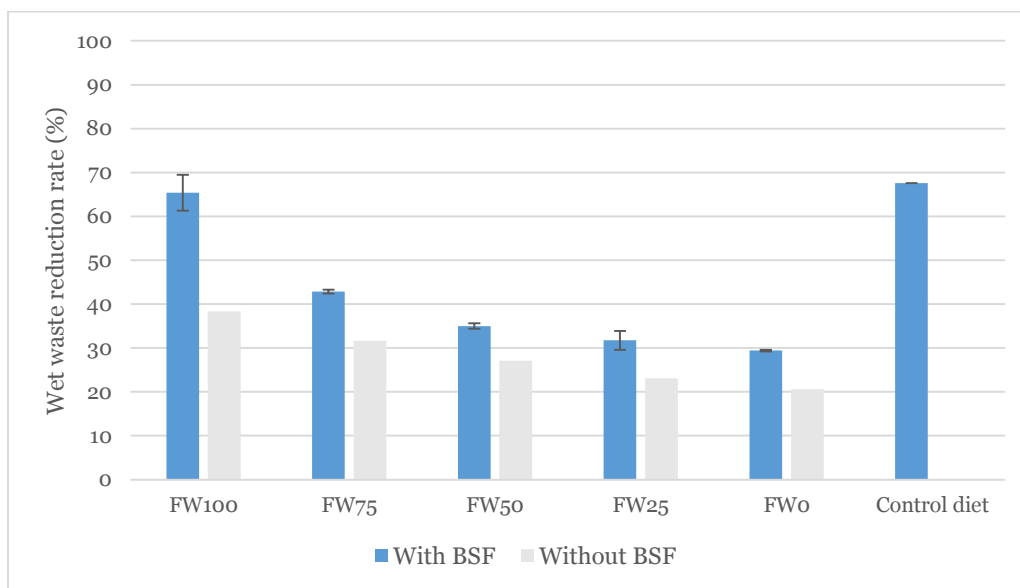


Figure 3.21 - Comparison of wet reduction rate with and without BSF larvae for different diets
Bars indicate standard deviations (n = 2)

Another parameter that could have influenced waste reduction rates is the presence of invasive filth fly larvae in some of the treatments which was due to the mesh used on the treatment containers being too coarse. Filth fly larvae were identified in most of the control treatments, as well as in some of the treatments with BSF larvae characterized by high larval mortality. However, Banks (2014), who experienced similar invasion, reported that waste reduction rate was not significantly influenced by the presence of filth fly larvae. Concerning bioconversion rates, as faecal sludge-based treatments were associated with high larval mortality rates and the absence of larval growth, these treatments resulted in very low bioconversion rates, or even zero bioconversion in some cases. As a result, bioconversion rate values do not significantly differ across the treatments containing faecal sludge, whether they were measured on wet or dry basis. By contrast, FW100 and the control diet were characterized by significantly higher bioconversion rates compared to faecal sludge-based treatments. In addition, compared to the control diet, FW100 exhibits a significantly higher bioconversion rate, i.e. approximately twice higher. Feed conversion ratio could not be calculated for faecal sludge-based treatments as no weight gain occurred. On the other hand, feed conversion ratios measured for FW100 and the control diet are not significantly different, whether measured on wet or dry basis.

Table 3.10 - Comparison of waste reduction, bioconversion, and feed conversion data obtained in this study with those reported in the literature

Feedstock	Waste reduction rate (%)		Bioconversion rate (%)		Feed conversion ratio		Reference
	Wet basis	Dry basis	Wet basis	Dry basis	Wet basis	Dry basis	
Food waste (FW100)	65	67	17.98	20.73	3.89	3.23	This study
Faecal sludge (FWo)	29	-	0.07	0.04	NA	NA	This study
Mixture of FW and FS (FW75,50&25)	32 - 43	1 - 22	0 – 0.007	0 – 0.05	NA	NA	This study
Fruit and vegetable waste	-	43 - 64	-	-	-	-	Saragi and Bagastyo (2015)
Municipal organic waste	46-76	66 - 79	-	11.78	-	14.5	Diener et al. (2011)
Fresh human faeces	25-55 ^a	73 ^b	2.1-18.1 ^a	-	2.0 – 15.6 ^a	-	^a Banks et al. (2014), ^b Lalander et al. (2013)
Pit latrine FS	30-39	-	-	3.5 – 6.4	-	-	Banks (2014)

In Table 3.10, waste reduction, bioconversion, and feed conversion values recorded in this study for the different diets are compared to those reported in the literature for similar feedstocks. Waste reduction rates estimated in this study for food waste (FW100) are comparable to those reported by Saragi and Bagastyo (2015) and Diener et al. (2011) for respectively fruit and vegetable waste, and municipal organic waste. In addition, more efficient bioconversion and feed conversion of food waste was observed in the present study than in the study of Diener et al (2011), probably due to the unfavourable conditions (high zinc concentration of the food and anaerobic conditions in the treatment trays) reported in the latter study. Despite high mortality and poor growth performance, treatments containing faecal sludge exhibit wet waste reduction rates similar to those reported for human waste by Banks (2014) and Banks et al. (2014). However, this could be due to the experiment having been conducted during the dry season. Therefore, dehydration of the substrate may have played a bigger part in waste reduction than in the other studies, conducted in temperate regions. This is supported by the fact that dry waste reduction rates obtained in this study for faecal sludge-based diets are much lower than that reported by Lalander et al. (2013) for fresh human faeces. On the other hand, due to high mortality and poor growth performance, bioconversion data recorded for the treatments containing faecal sludge are much lower than those reported by Banks et al. (2014) for fresh faeces. In this regard, studies by Lalander et al. (2013) and Banks et al. (2014) demonstrated that fresh human faeces can be converted using the BSF with performance similar to food waste. However, according to the values reported by Banks (2014), pit latrine faecal sludge seems to be associated with lower performance.

• Conclusion

Values obtained in this study for food waste compare positively with those reported in the literature for similar feedstocks, which confirms the technical feasibility of processing food waste via a low-tech BSF bioconversion system in Ghana. However, one limitation of the study is that it did not consider the variability of the food waste's composition as all the food waste used for the waste treatment trial was collected at once at the beginning of the experiment. Regarding faecal sludge, due to high mortality and absence of apparent development, in all the treatments containing faecal sludge, even in small amounts, the present study does not allow to conclude on the technical feasibility of converting faecal sludge alone or mixed with food waste using the BSF system designed. Therefore, further research is needed. Since it is hypothesized that poor performance recorded for the faecal sludge-based treatments is due to the use of dewatered faecal sludge whose structure after rehydration was not suitable for larval feeding, the present experiment should be replicated using raw or slightly dewatered faecal sludge. Another option that could be investigated is the use of structuring material such as crushed charcoal, as suggested by Perednia (2016).

3.3.3 Second waste treatment trial

- Larval survival rate, weight gain and development time

Figure 3.22 displays the weight gained over time by BSF larvae fed with eight different diets described in Section 3.2.5, while Table 3.11 shows larval survival rates, development times, as well as final larval and prepupal weights (measured on both wet and dry basis) for the different treatments.

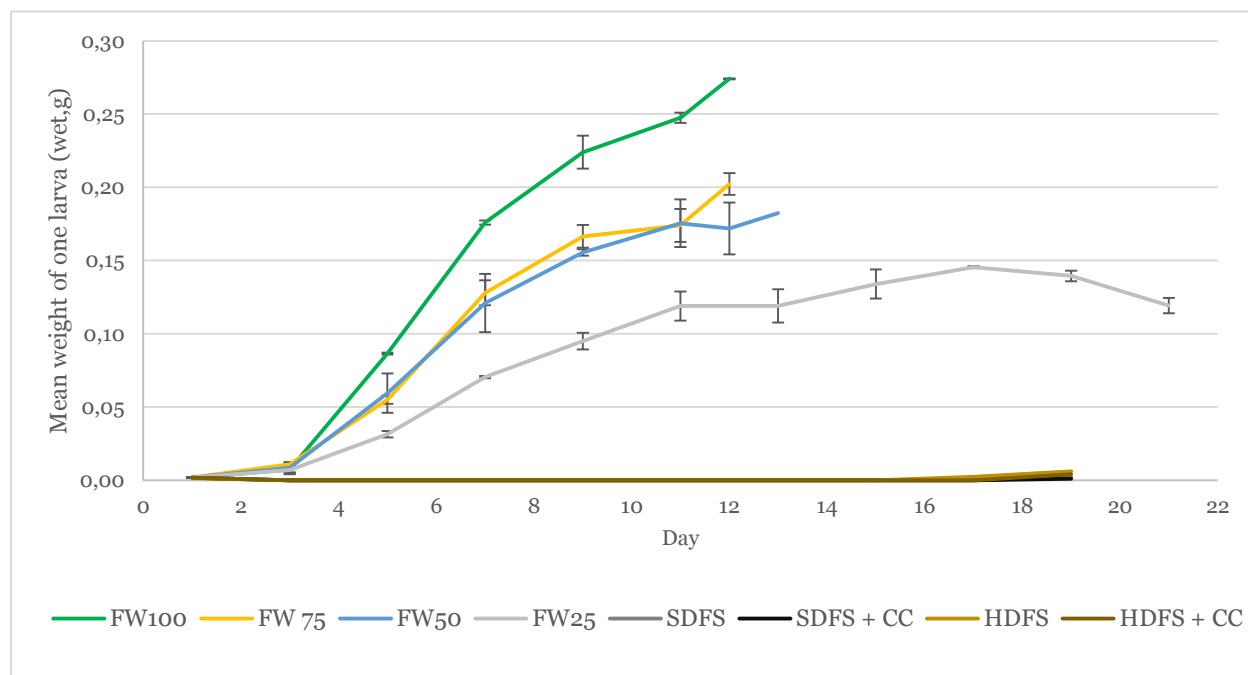


Figure 3.22 - Weight gained over time by BSF larvae fed with eight different diets consisting of food waste (FW100), mixtures of food waste and slightly dewatered faecal sludge in ratios 3:1 (FW75), 1:1 (FW50), 1:3 (FW25), slightly dewatered faecal sludge alone (SDFS) or mixed with charcoal (SDFS + CC), and rehydrated highly dewatered faecal sludge alone (HDFS) or mixed with charcoal (HDFS + CC). Bars indicate standard deviations (n = 2).

Table 3.11 - Survival rates, development times, larval and prepupal weights of BSF fed with different food waste and faecal sludge-based diets

Diet	Larval survival rate (%)	Larval development time (days)	Larval weight at the end of the feeding period (g)		Prepupa weight (g)	
			Wet basis	Dry basis	Wet basis	Dry basis
FW100	99.5 ± 0.71 ^a	12.0 ± 0.0 ^a	0.27 ± 0.00 ^a	0.11 ± 0.01 ^a	0.18 ± 0.00 ^a	0.08 ± 0.00 ^a
FW 75	98.0 ± 2.83 ^a	12.0 ± 0.0 ^a	0.20 ± 0.01 ^b	0.08 ± 0.00 ^b	0.14 ± 0.01 ^b	0.06 ± 0.00 ^b
FW50	99.2 ± 0.24 ^a	12.5 ± 0.7 ^a	0.18 ± 0.01 ^c	0.07 ± 0.00 ^b	0.13 ± 0.01 ^b	0.05 ± 0.00 ^b
FW25	85.0 ± 8.01 ^a	21.0 ± 0.0 ^b	0.12 ± 0.01 ^d	0.04 ± 0.01 ^c	0.10 ± 0.00 ^c	0.04 ± 0.00 ^c
SDFS	18.5 ± 8.7 ^b	No development	0.00 ± 0.00 ^e	0.00 ± 0.00 ^d	No prepupa	No prepupa
SDFS + CC	12.8 ± 14.85 ^b	No development	0.00 ± 0.00 ^e	0.00 ± 0.00 ^d	No prepupa	No prepupa
HDFS	11.2 ± 3.06 ^b	No development	0.01 ± 0.00 ^e	0.00 ± 0.00 ^d	No prepupa	No prepupa
HDFS + CC	40.0 ± 14.61 ^b	No development	0.00 ± 0.00 ^e	0.00 ± 0.00 ^d	No prepupa	No prepupa

Values are reported as mean ± standard deviation (n = 2). Mean values followed by the same letter in the same column do not differ significantly (P > 0.05).

As in the first experiment, FW100 (100% food waste) was associated with the highest development performance since it resulted in the greatest larval and prepupal weights (mean dry prepupal weight: 0.08 g) in the shortest time (mean development time: 12 days), as well as the highest larval survival rate (mean survival rate: 100%) (see Table 3.11). The results recorded for FW100 in the present experiment are similar to those reported in the first experiment (see Table 3.7). The larval survival rate in the present experiment is slightly higher, while the larval development time is 0.5 day shorter than that reported in the first experiment. Similarly, compared to the first experiment, a slightly higher larval weight but lower prepupal weight were recorded in the second experiment. This indicates the replicability of the first experiment with regards to the food waste treatment.

As shown in Figure 3.22, the larvae fed on the different mixtures of food waste and slightly dewatered faecal sludge (i.e. FW75, FW50, and FW25) experienced significant growth, allowing them to reach the prepupal stage. In addition, these treatments resulted in high larval survival rates, which were not significantly different from that recorded for FW100. This contrasts with the results from the first experiment in which the larvae fed with mixtures of food waste and rehydrated highly dewatered faecal sludge did not experience any growth and show a high mortality. Therefore, this supports the hypothesis according to which the poor development performance recorded in the first experiment for FW75, FW50, and FW25 were due to the faecal sludge having been highly dewatered before being fed to the larvae. Comparing development performance of FW75, FW50, and FW25 (see Figure 3.22 and Table 3.11) shows that the higher the proportion of food waste, the fastest larvae reach the prepupal stage and the heaviest they are. Indeed, among the diets containing both food waste and faecal sludge, FW75 (75% of food waste) was associated with the shortest development time (mean development time: 12 days) and the highest larval and prepupal weights (mean dry prepupal weight: 0.06 g), while FW25 (only 25% of food waste) resulted in the lightest larvae and prepupae (mean dry prepupal weight: 0.04 g) in the longest time (mean development time: 21 days). However, a clear difference in performance appears between FW75 and FW50, on the one hand, and FW25, on the other hand. Except for wet larval weight, results pertaining to larval development recorded for FW75 and FW50 were not significantly different (see Table 3.11). By contrast, compared to FW75 and FW50, FW25 exhibited significantly poorer development performance. Regarding the effect of co-digesting food waste and faecal sludge, including up to 50% of faecal sludge in the larvae's diet did not result in significant difference in terms of larval survival rate and development time, compared to FW100. However, the inclusion of as little as 25% faecal sludge yielded significantly lighter larvae and prepupae. On the other hand, development performance recorded for FW75 and FW50 compare positively with those reported for wheat bran (control diet) in the first experiment, as well as values reported in the literature for food waste and human waste. Therefore, co-digesting food waste with up to 50% of faecal sludge yields satisfactory results with regards to larval development. However, the significantly different development performance recorded for FW75 and FW50, on the one hand, and FW25, on the other hand, indicates the existence of a threshold for the inclusion of faecal sludge, which lies between 50% and 75%, and beyond which development performance declines significantly.

While larvae fed mixtures of food waste and faecal sludge in varying ratios developed and turned into prepupae, larvae fed only faecal sludge, either slightly dewatered (SDFS) or highly dewatered (HDFS), did not show any apparent growth. The exception being HDFS treatment for which the mean larval weight seems to increase at the end of the feeding period (see Figure 3.22). However, this is due to a piece of fruit which was found in one of the HDFS replicates and was probably initially present in the dry faecal sludge collected at the composting plant. A few significantly bigger larvae were found inside the piece of fruit waste at the end of the experiment, which explains the increase in larval weight in HDFS at the end of the feeding period. In addition, SDFS and HDFS were associated with high mortality rate. Moreover, when comparing faecal sludge-based diets with and without crushed charcoal (i.e. SDFS and HDFS on the one hand, and SDFS + CC and HDFS + CC on the other hand), no significant difference was recorded, indicating that the addition of crushed charcoal had no apparent effect on larval development performance for the faecal sludge treatments.

- Waste reduction rate, bioconversion rate, and feed conversion ratio

Table 3.12 presents the waste reduction rate, bioconversion rate, and feed conversion ratio for each diet.

Table 3.12 - Waste reduction rates, bioconversion rates, and feed conversion ratios for different food waste and faecal sludge-based diets

Diet	Waste reduction rate (%)	Bioconversion rate (%)		Feed conversion ratio (%)	
	Wet basis	Wet basis	Dry basis	Wet basis	Dry basis
FW100	61.37 ± 0.78 ^a	18.09 ± 0.68 ^a	28.52 ± 3.57 ^a	3.42 ± 0.18 ^a	2.18 ± 0.24 ^a
FW 75	59.53 ± 0.18 ^a	12.05 ± 0.48 ^b	19.87 ± 3.24 ^b	5.01 ± 0.03 ^a	3.06 ± 0.51 ^a
FW50	67.72 ± 6.57 ^a	12.17 ± 0.44 ^b	17.27 ± 1.04 ^b	5.63 ± 0.18 ^a	3.94 ± 0.14 ^a
FW25	61.49 ± 3.58 ^a	4.39 ± 0.18 ^c	6.31 ± 3.69 ^c	14.5 ± 2.81 ^b	12.11 ± 7.68 ^a
SDFS	25.89 ± 0.15 ^b	0.02 ± 0.00 ^d	0.01 ± 0.01 ^c	No weight gain	No weight gain
SDFS + CC	22.93 ± 0.50 ^b	0.01 ± 0.00 ^d	0.00 ± 0.00 ^c	No weight gain	No weight gain
HDFS	24.18 ± 0.15 ^b	0.03 ± 0.00 ^d	0.02 ± 0.03 ^c	No weight gain	No weight gain
HDFS + CC	20.93 ± 0.43 ^b	0.09 ± 0.00 ^d	0.03 ± 0.02 ^c	No weight gain	No weight gain

Values are reported as mean ± standard deviation (n = 2). Mean values followed by the same letter in the same column do not differ significantly (P > 0.05).

As in the first experiment, errors occurred when estimating dry waste reduction rates. Therefore, waste reduction rates are only presented on wet basis. Wet waste reduction rates do not vary significantly across treatments containing food waste, and compare positively with values reported in the literature both for food waste and human waste (see Table 3.10). However, waste reduction values calculated for FW50 and FW25 may be lower in reality since matter was lost when washing larvae covered with sludge to identify their stage of development. By contrast, wet waste reduction rates recorded for food waste-based treatments are significantly higher than those reported for treatments containing only faecal sludge, either slightly or highly dewatered, and with or without charcoal. For these latter treatments, waste reduction rates obtained experimentally are lower than those reported in the literature for fresh human faeces and pit latrine faecal sludge. Regarding bioconversion rates, the higher the proportion of food waste, the greater the bioconversion rate, a trend observed both on wet and dry basis. However, wet and dry bioconversion rates recorded for FW75 and FW50 are not significantly different, but are significantly higher than that reported for FW25, indicating once again a performance threshold for biomass production between 50 and 75% of faecal sludge. Experimental bioconversion values for FW100, FW75, and FW50 compare positively with those reported in the literature for municipal organic waste, while those for FW25 are within the range reported for human waste (see Table 3.10). On the other hand, as larvae fed with only faecal sludge did not show any growth, bioconversion rates associated with these treatments are almost zero. Finally, dry feed conversion ratios do not vary significantly across treatments containing food waste and compare positively to value reported in the literature both for municipal organic waste and fresh human faeces.

While mixing faecal sludge to food waste yielded results in terms of biomass production and waste reduction that were comparable to values reported in the literature for food waste and/or human waste, poor bioconversion performance was recorded when treating faecal sludge alone. This contrasts with studies on fresh human faeces and pit latrine faecal sludge which reported satisfactory bioconversion performance for these substrates. Performance differences may be due to the type of faecal sludge that was used in this experiment. It consisted of a mixture of septic tank and pit latrine faecal sludge. While water is generally not added in pit latrines, the faecal sludge in septic tank is largely diluted. Therefore, the faecal sludge used in this experiment was less concentrated and probably much poorer in nutrients compared to the fresh faeces and pit latrine faecal sludge analysed in the other studies. This could be confirmed by analysing the nutrient content of the input faecal sludge and compare it to values reported by other studies on human waste.

- Conclusion

This experiment enabled establishing that co-digesting food waste and faecal sludge with BSF was technically feasible. However further research is required to characterize the bioconversion products, especially the nutritional value of the final larval biomass and the nutrient content of the waste residue, as well as determine the optimal food waste/faecal sludge ratio and estimate a more precise threshold value for the inclusion of faecal sludge. On the other hand, the feasibility of processing faecal sludge from septic tanks and pit latrines alone with BSF could not be established in this study.

Chapter 4: Assessing the Economic Viability of a Low-tech Black Soldier Fly Bioconversion System for Food Waste and Faecal Sludge in Ghana

4.1 Background information for the economic analysis

As revealed by the literature review (see sections 2.2.3 and 2.2.5), few studies address the economic aspect of BSF waste treatment. In particular, to date, the economic viability of small and medium-scale BSF treatment plants, i.e. treating less than 100 tonnes of waste per day, has not been established. However, the literature suggests that BSF waste treatment may be more interesting from an economic point of view than conventional treatment methods for organic waste, i.e. composting and anaerobic digestion. For example, Lalander et al. (2017), when comparing the value of the products of thermophilic composting, anaerobic digestion, and BSF treatment of both food waste and faecal sludge, in the Swedish context, demonstrated that BSF treatment yielded the highest value products. Similarly, Diener et al. (2014) compared the potential market value of different products derived from the valorisation of faecal sludge, i.e. fuel combustion, BSF proteins, fuel biogas, and soil conditioner, in different Sub-Saharan African cities, including Accra. They assessed that, in Accra, BSF proteins and biogas exhibit the highest potential market value. However, these different authors could not conclude on the most viable option as they did not take into account costs associated with each technology. In this regard, as BSF thrives in tropical regions, BSF technology can be implemented at relatively low-cost in those areas, making it a potentially viable option in the Ghanaian context. However, this needs to be established as limited data are available on the economic performance of the few small-scale BSF systems implemented in Greater Accra as part of research projects.

4.2 Methods and materials for the economic analysis

A comparative cost-benefit analysis (CBA) was conducted in order to assess the economic viability of a low-tech BSF bioconversion system for food waste and faecal sludge in Ghana. The main steps followed as part of the CBA are illustrated in Figure 4.1.

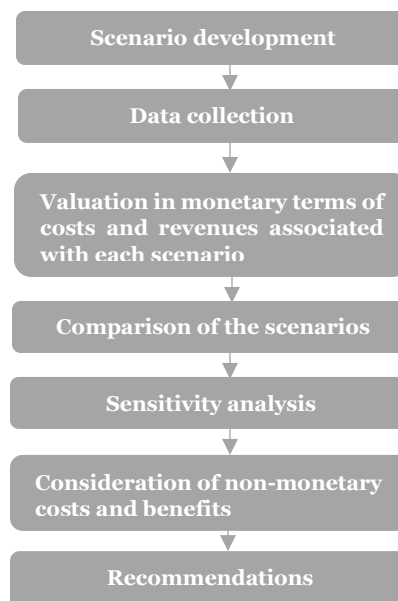


Figure 4.1 - Steps of the economic assessment conducted

4.2.1 Scenario development

Three scenarios were analysed as part of the CBA, namely (1) composting scenario; (2) BSF scenario; and (3) BSF + composting scenario. They are described below.

○ Composting scenario

The composting scenario was used as a reference as it is currently the main valorisation method for food waste and faecal sludge in Ghana, and, more generally, it constitutes a common treatment option for organic waste worldwide. The flowchart associated with the composting scenario is presented in Figure 4.2.



Figure 4.2 - Flowchart for the composting scenario

In addition, Figure 4.3 illustrates the different components of the composting facility considered in this scenario. Because of its high moisture content, the faecal sludge received at the composting facility is first dried for about 10 days in sand drying beds, a low-tech method adapted to the Ghanaian context. Sorted food waste is then co-composted with dewatered faecal sludge (mass ratio of 3:1) in a windrow system for about two months. After two months, the compost undergoes a maturation phase for an additional month. Once matured, the compost is sieved and bagged. In this scenario, one product is yielded, namely organic fertilizer.

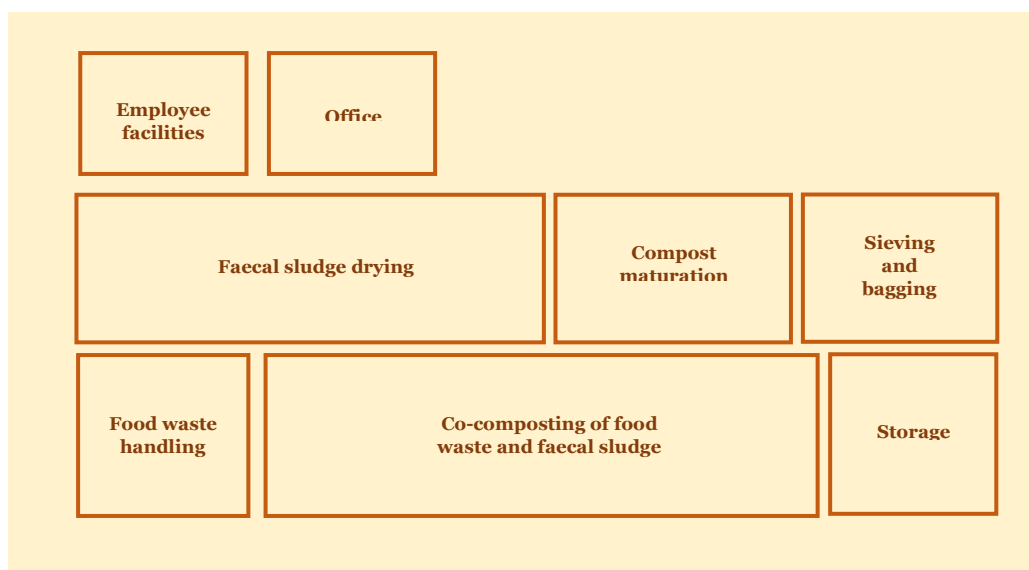


Figure 4.3 - Schematic representation of the facility considered in the composting scenario

○ BSF scenario

The flowchart associated with the BSF scenario is presented in Figure 4.4, while the different components of the system considered are illustrated in Figure 4.5.

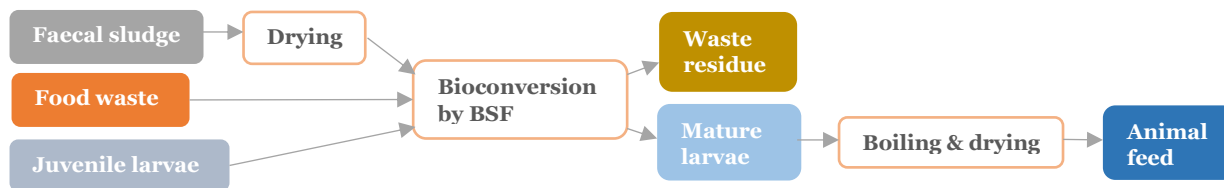


Figure 4.4 - Flowchart for the BSF scenario

As in the composting scenario, faecal sludge is first dried in sand drying bands to reduce its moisture content. However, unlike in the composting scenario, the drying process only lasts three days since it was established in the technical feasibility study that slightly dewatered faecal sludge is suitable for BSF digestion but not highly dewatered faecal sludge (see section 3.3.3). After drying, faecal sludge is mixed with food waste in a mass ratio of 1:3 (value established in the 2nd waste treatment trial, see section 3.3.3). Then, the mixture is digested by BSF in the waste treatment unit, while juvenile larvae used to process the waste are produced in the rearing unit. Mature larvae are post-processed but not the waste residue. Therefore, in this scenario, only one valuable product is yielded, namely BSF larvae for animal feeding.

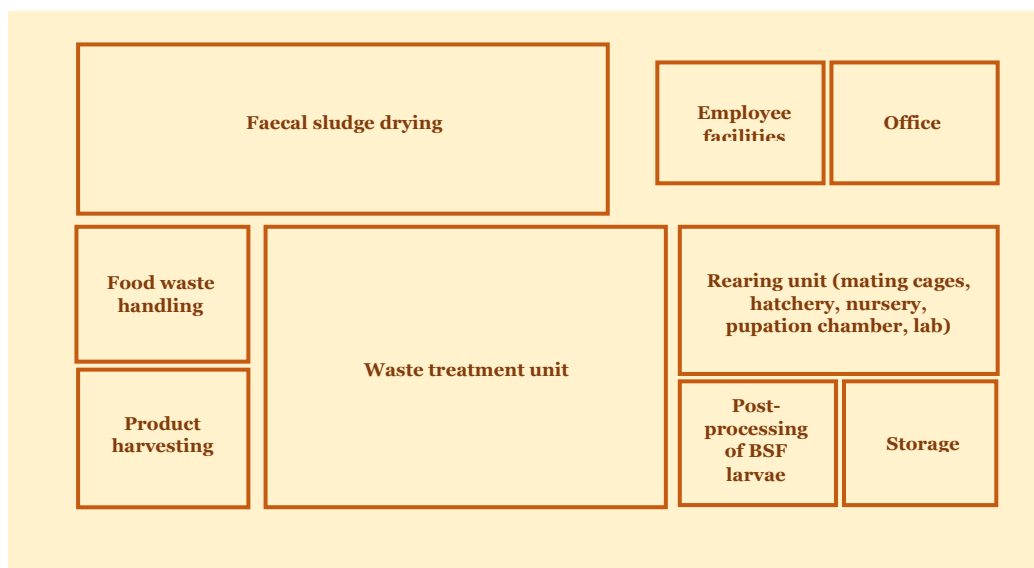


Figure 4.5 - Schematic representation of the facility considered in the BSF scenario

- BSF + composting

The flowchart associated with the BSF + composting scenario is presented in Figure 4.6. This scenario is similar to the BSF scenario, with one difference being that the waste residue is composted to yield a second valuable product.

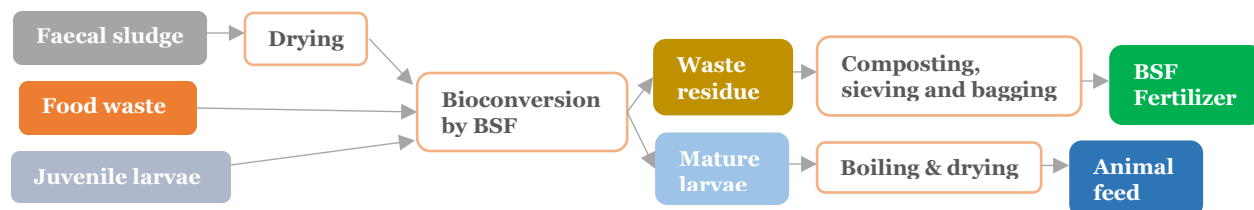


Figure 4.6 - Flowchart for the BSF + composting scenario

As illustrated in Figure 4.7, the facility considered in this scenario includes the same components as that in the BSF scenario, as well as an additional unit where the waste residue is composted to reach maturity.

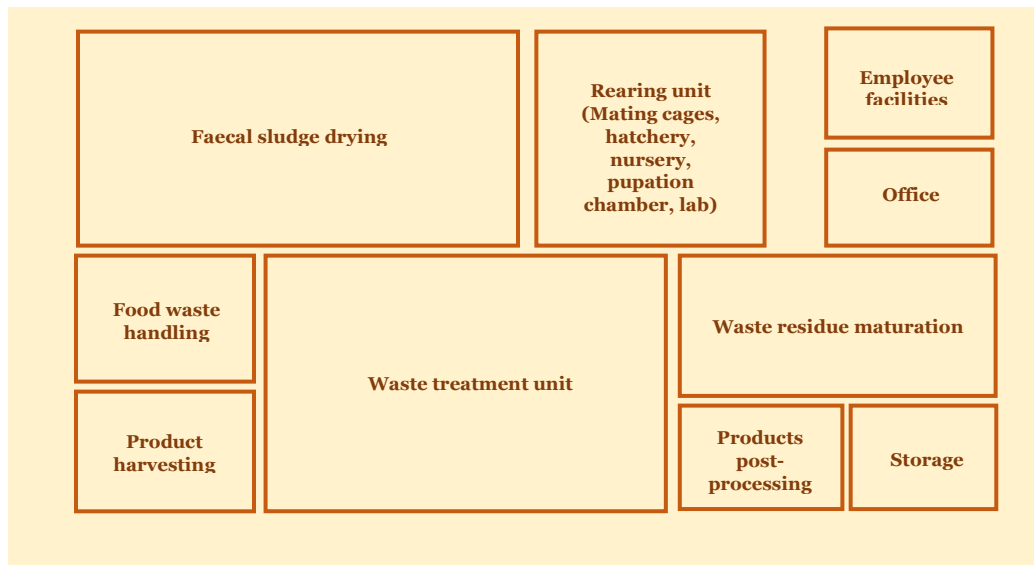


Figure 4.7 - Schematic representation of the facility considered in the BSF + composting scenario

Despite the potential high market value of biogas in Accra (Diener et al., 2014), the anaerobic digestion scenario was not taken into account in this study because of the high investment and operating costs associated with this technology, which hinders its implementation in cities, like Accra, which have limited financial resources. Similarly, the option which consists of producing biodiesel from BSF larvae was not considered since, to the author's best knowledge, this post-processing technology has only been tested experimentally and no economic data is available.

4.2.2 Data collection

For the composting scenario, data were mainly extrapolated from the case study of the *Fortifier™* composting plant in Tema Metropolis (Greater Accra). Data pertaining to the *Fortifier™* plant were provided by IWMI and Jekora Ventures Ltd (JVL). For the BSF-based scenarios, experimental data collected during the field work were used. Data that could not be obtained experimentally were obtained from the literature or case studies documented as part of the review of BSF technology (see section 2.2.4).

4.2.3 Valuation of costs and revenues in monetary terms

For each scenario, calculations were based on a functional unit of 1 tonne of waste per day. Costs considered in the analysis can be broken down in three categories, namely investment costs, production costs, and other running costs, while two sources of revenue were considered, i.e. the sales of the product(s), and tipping fees paid by private truck operators transporting faecal sludge. Quantification of the various costs and revenues associated with each scenario was based on the following main assumptions:

- (1) For all three scenarios, low-tech systems were considered. Therefore, operations such as feedstock preparation, sieving, and bagging of the products were assumed to be performed manually. In addition, low-tech techniques (boiling and sun drying) were considered for the post-processing of mature larvae in the BSF and BSF + composting scenarios.
- (2) Investment costs considered in the analysis include building and construction costs, equipment and machinery costs, and legal and registration costs. Costs pertaining to land acquisition were not taken into account as it was assumed that a composting and/or BSF facility could benefit from a land provided by the municipality in which it operates.
- (3) Production costs considered include costs pertaining to labour, consumables, water and electricity.
- (4) For the labour costs, in addition to full-time operators, it was assumed that a plant manager was employed on a part-time basis (4 hours/week) to supervise the operation of the facility.
- (5) Other costs considered include costs pertaining to operation and maintenance, product certification, equipment and building depreciation, and income tax. Operation and maintenance costs were assumed to amount to 5% of the equipment and machinery's value and 0.05% of building costs. A straight-line model was assumed for depreciation costs calculation.
- (6) Costs pertaining to waste transport were not taken into account in this analysis. It was assumed that the waste treatment plant could be operated by a private waste management company already providing collection service for municipal organic solid waste. In addition, faecal sludge was assumed to be transported by private operators, as it is mostly the case in Greater Accra region.
- (7) Financing costs, costs for handling the waste from the process (e.g. inorganic waste, and the waste residue in BSF scenario), and marketing costs were not taken into account.
- (8) For the revenues, the selling price of the products were estimated based on the price of similar products on the Ghanaian market.
- (9) It was assumed that the selling price of the products and other input costs were subjected to an escalation of 12.4%, which corresponds to the mean inflation rate over the year 2017 in Ghana (Trading Economics, 2018a).
- (10) The lifetime of the waste treatment facility in each scenario was assumed to be ten years.

All base values used for the calculation of costs and revenues associated with each scenario, as well as a detailed account of the methods used for the calculations can be respectively found in Appendices A and B.

4.2.4 Comparison of the three scenarios

Financial viability results were analysed in terms of three economic indicators commonly used in CBA of waste-related projects, namely Net Present Value (NPV), Benefit Cost Ratio (BCR), and Internal Rate of Return (IRR) (Pandyaswargo and Premakumara, 2014; Ćetković et al., 2017).

The NPV is defined as the difference between the discounted benefits and discounted costs over the scenario's lifetime (see Equation (8)).

$$NPV = \sum_{t=0}^T \frac{B_t - C_t}{(1 + r)^t} \quad (8)$$

with T the lifetime of the plant, B_t the benefits in year t, C_t the costs in year t, and r the discount rate. The discount rate enables taking into account the time value of money, i.e. the further a benefit or cost is in the future, the lower its value. A positive NPV indicates that the scenario is viable. The scenario with the highest NPV represents the most profitable option. The BCR is the ratio of the discounted benefits versus discounted costs over the scenario's lifetime (see Equation (9)).

$$BCR = \frac{\sum_{t=0}^T B_t (1 + r)^{-t}}{\sum_{t=0}^T C_t (1 + r)^{-t}} \quad (9)$$

Notations are the same as for the NPV. A scenario is viable if its BCR exceeds 1. The IRR corresponds to the discount rate at which the NPV of the scenario equals zero (see Equation (10)). If the IRR is greater than the selected discount rate, the scenario is considered viable. The lower the IRR, the riskier the scenario.

$$\sum_{t=0}^T \frac{B_t - C_t}{(1 + IRR)^t} = 0 \quad (10)$$

A discount rate of 5.7% was assumed. It corresponds to the average market interest rate in Ghana over the period 2002-2018 (18.1%) minus the average inflation rate in Ghana over 2017 (12.4%) (Trading Economics, 2018a&b), a calculation method used by Lai and Strasma (1992).

4.2.5 Sensitivity analysis

To assess the sensitivity of the indicators considered to variations in the models input parameters, a Monte Carlo simulation was conducted. Such method enables taking into account the uncertainty associated to several input parameters simultaneously. Table 4.1 presents for each scenario the parameters that were considered uncertain and the probabilistic distribution assumed for each of these parameters

Table 4.1 - Distributions defined for the input parameters in Monte Carlo simulation

Parameter	Distribution	Min	Mode	Max	Unit
All scenarios					
Building cost per area	Triangular	120	335	550	GHS/m ²
Operator salary	Triangular	500	700	900	GHS/month/operator
Discount rate	Uniform	5	10	15	%
Composting scenario					
Labour requirement	Triangular	2	4	6	Operators/tonne of daily input
Composting and BSF + composting scenarios					
Compost price	Triangular	0.30	0.50	0.70	GHS/kg compost
BSF and BSF + composting scenario					
Price of BSF larvae	Triangular	2.00	4.00	5.89	GHS/kg dry larvae

As shown in Table 4.1, building cost per area was assumed to vary according to a triangular distribution between 120 GHS/m² and 550 GHS/m², which correspond approximately to the building cost per area in respectively Ento-Prise and *Fortifier*TM case studies. Operators' salary was assumed to vary according to a triangular distribution between 500 and 900 GHS/month/operator. As an indication, the monthly minimum wage in Ghana has been set at 261 GHS/month for 2018 (Mywage.org/Ghana, 2018). As NPV and BCR values depend on that of the discount rate. It was assumed that it varies uniformly between 5% and 15%. Labour requirement for composting was also chosen as an uncertain parameter as a wide range of values was found in the literature for this variable. In addition, the value assumed in the first part of the analysis (i.e. 3 operators/tonne of daily input) was extrapolated from *Fortifier*TM case study without taking into account that this plant is more mechanized than that assumed in the composting scenario, and thus its operation may be less labour intensive. Compost price was assumed to vary according to a triangular distribution between 0.3 GHS/kg (the lowest price for organic fertilizer on the Ghanaian market) and 0.70 GHS/kg (a price between that of *Fortifier*TM compost and conventional fertilizers) (see Table 5.17). Similarly, it was assumed that the price of dry BSF larvae varies according to a triangular distribution between 2.00 GHS/kg of dry larvae (price of soybean) and 5.89 GHS/kg of dry larvae (price of high grade fishmeal) (see Table 5.18), as these feed products are commonly used in the literature to set the price of BSF larvae. Finally, 10,000 iterations were run for each scenario in order to obtain relatively stable results.

4.3 Results for the economic analysis

- Financial results under the initial assumptions

Table 4.2, Table 4.3, and Table 4.4 present the financial results over 10 years for respectively the composting, BSF, and BSF + composting scenarios⁵.

⁵ Numbers in brackets indicate negative values

Table 4.2 - Financial results over 10 years for the composting scenario

Year	0	1	2	3	4	5	6	7	8	9	10
Investment costs											
Building and construction	459,641	-	-	-	-	-	-	-	-	-	-
Equipment and machinery	3,363	-	-	-	-	-	-	-	-	-	-
Legal and registration	20,052	-	-	-	-	-	-	-	-	-	-
Total investment	483,056	-	-	-	-	-	-	-	-	-	-
Revenue											
Compost sales	-	97,768	109,891	123,518	138,834	156,049	175,399	197,149	221,595	249,073	279,958
Tipping fees	-	7,333	8,242	9,264	10,413	11,704	13,155	14,786	16,620	18,680	20,997
Total revenue	-	105,100	118,133	132,781	149,246	167,753	188,554	211,935	238,215	267,753	300,955
Running costs											
Production costs											
Labour	-	28,200	31,697	35,627	40,045	45,011	50,592	56,865	63,917	71,842	80,751
Consumables	-	3,911	4,396	4,941	5,554	6,242	7,016	7,887	8,864	9,964	11,199
Water and electricity	-	1,137	1,278	1,436	1,614	1,815	2,040	2,293	2,577	2,896	3,256
Gross margin	-	71,853	80,762	90,777	102,033	114,685	128,906	144,891	162,857	183,051	205,750
Other costs											
Operation and maintenance	-	2,234	2,511	2,822	3,172	3,566	4,008	4,505	5,063	5,691	6,397
Product certification	1,900	-	-	1,900	-	1,900	-	1,900	-	1,900	-
Depreciation	-	8,465	8,465	8,465	8,465	8,465	8,465	8,465	8,465	8,465	8,465
Income tax	-	15,288	17,447	19,397	22,599	25,189	29,108	32,505	37,332	41,749	47,722
Total running cost	1,900	59,235	65,793	74,589	81,449	92,187	101,229	114,419	126,218	142,507	157,789
Net cash flow	(484,956)	45,865	52,340	58,192	67,797	75,566	87,325	97,516	111,996	125,246	143,166
Accumulative cash flow	(484,956)	(439,091)	(386,751)	(328,559)	(260,763)	(185,197)	(97,872)	(356)	111,640	236,887	380,052

Table 4.3 - Financial results over 10 years for the BSF scenario

Year	0	1	2	3	4	5	6	7	8	9	10
Investment costs											
Building and construction	130,608	-	-	-	-	-	-	-	-	-	-
Equipment and machinery	130,075	-	-	-	-	-	-	-	-	-	-
Legal and registration	20,052	-	-	-	-	-	-	-	-	-	-
Total investment	280,735	-	-	-	-	-	-	-	-	-	-
Revenue											
BSF larvae sales	-	65,843	74,007	83,184	93,499	105,093	118,124	132,772	149,235	167,740	188,540
Tipping fees	-	820	922	1,037	1,165	1,310	1,472	1,654	1,860	2,090	2,349
Total revenue	-	66,663	74,929	84,221	94,664	106,402	119,596	134,426	151,095	169,831	190,890
Running costs											
Production costs											
Labour	-	19,800	16,800	18,883	21,225	23,857	26,815	30,140	33,877	38,078	42,800
Consumables	-	3,955	4,445	4,996	5,616	6,312	7,095	7,975	8,964	10,075	11,325
Water and electricity	-	3,229	3,629	4,079	4,585	5,154	5,793	6,511	7,319	8,226	9,246
Gross margin	-	39,679	50,055	56,261	63,238	71,079	79,893	89,800	100,935	113,451	127,519
Other costs											
Operation and maintenance	-	7,091	7,970	8,958	10,069	11,318	12,721	14,298	16,071	18,064	20,304
Product certification	1,900	-	-	1,900	-	1,900	-	1,900	-	1,900	-
Depreciation	-	10,152	10,152	10,152	10,152	10,152	10,152	10,152	10,152	10,152	10,152
Income tax	-	5,609	7,983	8,813	10,754	11,927	14,255	15,862	18,678	20,834	24,266
Total running cost	1,900	49,836	50,980	57,782	62,402	70,620	76,831	86,839	95,061	107,330	118,093
Net cash flow	(282,635)	16,827	23,949	26,438	32,262	35,782	42,765	47,587	56,033	62,501	72,797
Accumulative cash flow	(282,635)	(265,808)	(241,858)	(215,420)	(183,158)	(147,376)	(104,612)	(57,025)	(991)	61,509	134,306

Table 4.4 - Financial results over 10 years for the BSF + composting scenario

Year	0	1	2	3	4	5	6	7	8	9	10
Investment costs											
Building and construction	191,719	-	-	-	-	-	-	-	-	-	-
Equipment and machinery	130,924	-	-	-	-	-	-	-	-	-	-
Legal and registration	20,052	-	-	-	-	-	-	-	-	-	-
Total investment	342,695	-	-	-	-	-	-	-	-	-	-
Revenue											
BSF larvae sales	-	65,843	74,007	83,184	93,499	105,093	118,124	132,772	149,235	167,740	188,540
Compost sales	-	39,572	44,478	49,994	56,193	63,161	70,993	79,796	89,691	100,812	113,313
Tipping fees	-	820	922	1,037	1,165	1,310	1,472	1,654	1,860	2,090	2,349
Total revenue	-	106,235	119,408	134,214	150,857	169,563	190,589	214,222	240,785	270,643	304,203
Running costs											
Production costs											
Labour	-	28,200	31,697	35,627	40,045	45,011	50,592	56,865	63,917	71,842	80,751
Consumables	-	4,388	4,932	5,544	6,231	7,004	7,873	8,849	9,946	11,179	12,566
Water and electricity	-	3,437	3,863	4,343	4,881	5,486	6,167	6,931	7,791	8,757	9,843
Gross margin	-	70,209	78,915	88,701	99,699	112,062	125,958	141,577	159,132	178,864	201,044
Other costs											
Operation and maintenance	-	7,408	8,326	9,359	10,519	11,824	13,290	14,938	16,790	18,872	21,212
Product certification	3,800	-	-	3,800	-	3,800	-	3,800	-	3,800	-
Depreciation	-	11,292	11,302	11,302	11,302	11,302	11,302	11,302	11,302	11,302	11,302
Income tax	-	12,877	14,822	16,060	19,469	21,284	25,341	27,884	32,760	36,223	42,132
Total running cost	3,800	67,603	74,943	86,035	92,448	105,711	114,565	130,570	142,506	161,975	177,806
Net cash flow	(346,495)	38,632	44,465	48,180	58,408	63,852	76,024	83,652	98,280	108,668	126,397
Accumulative cash flow	(346,495)	(307,863)	(263,398)	(215,218)	(156,810)	(92,958)	(16,933)	66,719	164,999	273,666	400,063

As shown in Table 4.2, Table 4.3, and Table 4.4, the composting scenario requires a significantly higher initial investment than the BSF and BSF + composting scenarios, due to a higher space requirement (~3.5 times higher than in the BSF scenario). In the composting scenario, building and construction costs make most of the initial investment, while in the BSF and BSF + scenario scenarios, the initial investment is more equally spread over building and construction costs, and equipment costs. In all three scenarios, sales of the products (compost and/or BSF larvae) account for most of the revenues generated by the plant, while in comparison tipping fees constitute a minor source of revenues, especially in the BSF and BSF + composting scenarios in which they account for only 1% of the revenues, compared to 7% in the composting scenario. In the BSF + composting scenario, sales of dry BSF larvae constitute the most important source of revenues as they represent about 62% of the revenues, while compost sales account for about 37% of the revenues. As it yields two products, the BSF + composting scenario is associated with the highest revenue. However, revenues generated in the composting and BSF + composting scenarios do not differ significantly. On the other hand, the revenue yielded in the BSF scenario is significantly lower (about 1.6 times lower than that in the composting and BSF + composting scenario). This is because, despite the higher selling price of dry BSF larvae (4.00 GHS/kg) compared to compost (0.50 GHS/kg), product yield is much lower in the BSF scenario than in the composting scenarios. Indeed, in the composting scenario about 540 kg of compost per day is produced from 1 tonne of daily waste input, while only 45 kg of dry larvae is obtained from the digestion of 1 tonne of waste by BSF larvae. Regarding running costs, production costs account for about 55% in all three scenarios. Especially, labour represents a major cost, as it accounts for 40-48% of the total running cost, depending on the scenario. By contrast, expenditure related to consumables, water, and electricity only accounts for about 9% in the composting scenario, and 14% in the BSF scenario. Calculation of net cash flows indicates that all three scenarios generate a profit from the first year of operation. However, due to relatively high initial investments, the pay-back period is quite long as it is at least 7 years for all scenarios. The BSF + composting scenario exhibits the shortest pay-back period, i.e. 7 years, since it generates the highest annual revenue and requires a lower investment than the composting scenario. In comparison, the initial investment is only amortized in year 8 in the composting scenario, and in year 9 in the BSF scenario. Regarding the overall financial performance, Table 4.5 compares NPV, BCR, and IRR calculated for each scenario under the initial assumptions.

Table 4.5 - NPV, BCR, and IRR of the 3 scenarios under the initial assumptions

	Composting scenario	BSF scenario	BSF+ composting scenario
NPV (GHS)	125,084	4,198	393,664
BCR	1.10	1.01	1.26
IRR (%)	9.9	6.0	13.4

As displayed by Table 4.5, given the initial assumptions, all three scenarios are financially viable as they are all associated with a positive NPV, a BCR greater than 1, and an IRR greater than the assumed discount rate (5.7%). BSF + composting scenario is associated with the highest NPV, BCR, and IRR. Therefore, given the assumption made, the BSF + composting scenario is the most profitable scenario. The second most profitable scenario is the composting scenario, with a NPV about three times lower than that of BSF + composting scenario. The least profitable scenario is the BSF scenario which is associated with a much lower NPV compared to the former scenarios. In addition, under this latter scenario, the BCR is very close to 1 which indicates a fragile economic viability.

- Sensitivity analysis

The results of the sensitivity analysis performed are presented in Table 4.6 and Figure 4.8. Table 4.6 shows, for each scenario, the mean, minimum, maximum, and standard deviation values of the NPV, BCR, and IRR for the 10,000 simulations run.

Table 4.6 - Results of the sensitivity analysis (mean, min, and max of the NPV, BCR, and IRR)

	Mean value	Minimum value	Maximum value	Standard deviation
Composting scenario				
NPV (GHS)	116,744	(371,438)	678,227	147,170
BCR	1.12	0.64	1.78	0.15
IRR (%)	16%	-15%	54%	8%
BSF scenario				
NPV (GHS)	(36,817)	(318,328)	337,578	92,565
BCR	0.94	0.50	1.38	0.13
IRR (%)	6%	-33%	26%	8%
BSF + composting scenario				
NPV (GHS)	205,235	(175,320)	769,780	140,302
BCR	1.21	0.76	1.63	0.13
IRR (%)	21%	-4%	45%	6%

Numbers in brackets indicate negative values

The BSF + composting scenario exhibits the highest mean values for all three indicators, followed by the composting scenario. For these two scenarios, mean NPV and BCR exceed respectively 0 and 1, which indicates that on average they are financially viable. By contrast, BSF scenario, which is associated with the lowest mean values for all three indicators has a negative mean NPV and a mean BCR lower than 1, which means that on average this scenario is not financially viable. Minimum, maximum, and standard deviation values of the different indicators indicate that simulation results are more scattered for the composting scenario than for the two other scenarios, showing a greater variability.

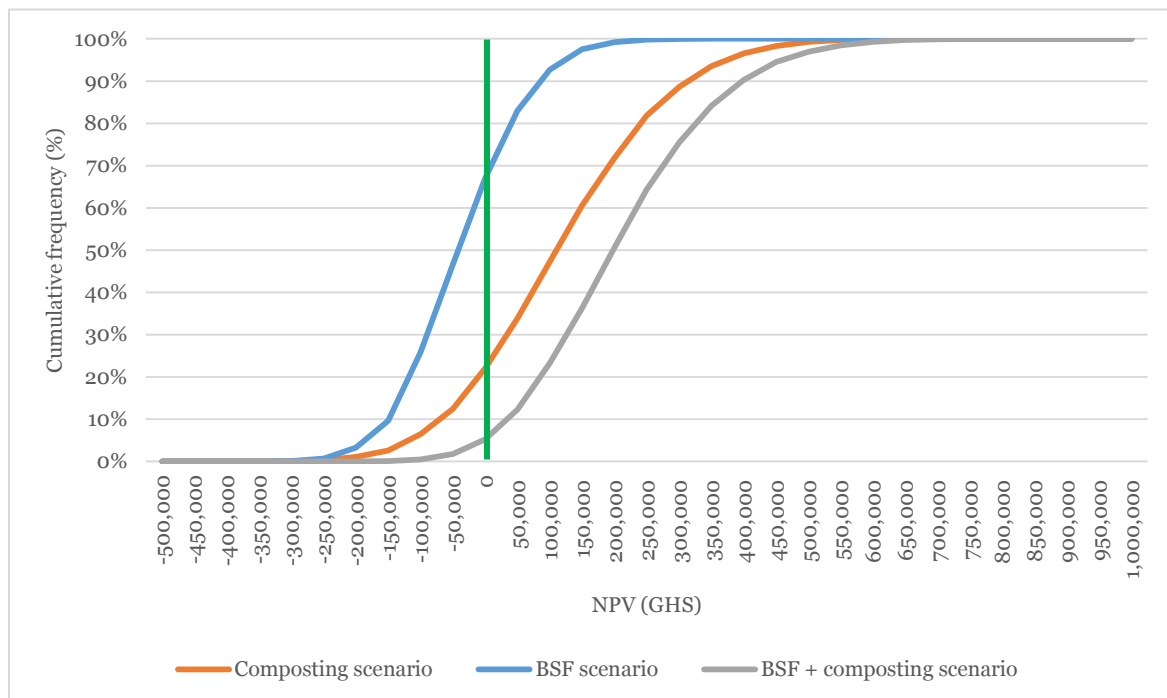


Figure 4.8 - Probability density functions of NPV for the three scenarios

Figure 4.8 shows the probability density functions of NPV for the three scenarios. It enables reading the probability, for each scenario, that the NPV is positive, i.e. the probability that the scenario is viable. This probability is 95% for the BSF + composting scenario, 78% for the composting scenario, and only 33% for the BSF scenario.

4.4 Discussion for the economic analysis

Based on the financial results and the sensitivity analysis, the BSF + composting scenario is the most likely to generate the highest profit, followed by the composting scenario, while BSF scenario exhibits the lowest probability to be profitable. However, to conclude on the viability of the different scenarios and formulate recommendations regarding the best scenario in the Ghanaian context, additional aspects should be considered. First, a number of the model input parameters for the BSF and BSF + composting scenarios were quantified based on experimental data. However, technical performance of the BSF system considered may be optimized, which would result in better economic performance for these scenarios. In addition, the analysis was based on the functional unit of 1 tonne of waste per day. Considering facilities with higher capacity may result in better financial results due to the economy of scale. Another important consideration is that it was assumed that the plant was able to sell its entire production. However, this is a strong assumption, especially in the case of compost. Indeed, Ghanaian farmers are reluctant to buy organic compost despite some advantages over inorganic fertilizer such as its lower price and its capacity to improve soil structure. Factors contributing to farmers' unwillingness to buy compost include the large quantity of compost needed on farm due to its bulkiness and the greater labour intensity required for its application (Drechsel and Kunze, 2011). To improve compost's marketability, Nikiema et al. (2013a) suggested pelletizing it, but this would require additional investments. By contrast, Diener et al. (2014) established that the market demand for BSF proteins in Accra was much higher than that for compost. However, despite the significant market demand for animal feed ingredients in Ghana, there may be challenges with consumer acceptance regarding proteins derived from faecal sludge (Agrawal et al., 2011; Popoff et al., 2017). This may also constitute a challenge for marketing faecal sludge-based compost (Nartey, 2013), but probably to a lesser degree. Regarding the BSF + composting scenario, very few studies have established the efficiency of the BSF compost as fertilizer. In particular, no study was found on the properties of compost produced from the waste residue from the co-digestion of faecal sludge and food waste by BSF. Therefore, it is not known whether the quality of BSF compost is equivalent to that of conventional compost, and thus if it can be sold at the same price, which was however assumed in this analysis. In this regard, if BSF compost proves to be marketable, BSF + composting scenario by yielding two products may be more resilient to market volatility than the other two scenarios, since, as pointed out by Murray (2016), market demands for compost and animal feed are probably not correlated.

In addition, the results presented focus on the financial viability of the scenarios, i.e. the costs and benefits to the enterprise operating the plant, rather than on the economic viability, i.e. the costs and benefits for the society as a whole. Therefore, to conclude on the economic viability of the different scenarios and compare them, non-financial aspects should be considered, including social and environmental consideration. For example, the compost scenario enables treating nine times more faecal sludge in volume than the BSF and BSF + compost scenarios. Considering the significant adverse health and environmental impacts associated with the direct release of faecal sludge into the environment, this could play in support of the composting scenario. On the other hand, substituting feed products conventionally used in the animal production industry, such as fishmeal and soybean meal, by BSF larvae-based feed ingredients could significantly improve the sustainability of this sector. Indeed, high environmental and social impacts are associated with the production and distribution of conventional feed ingredients. They include pressure on land availability for human food production, deforestation, reduction of biodiversity and soil fertility, pressure on water and wild fish resources, and air pollution due to long-distance transport (Papadoyianis, 2007; Tacon and Metian, 2008; Stamer, 2015; Sprangers et al., 2017). In this regard, Smetana et al. (2016), who conducted a life cycle assessment of insect production for feed manufacturing, estimated that producing insect-based meals from high-impacting waste streams or low value food processing by-products is two to five times more environmental-friendly than manufacturing conventional feed products.

Another advantage of BSF waste treatment method over composting is the lower CO₂ emissions. Perednia (2017) established that, compared to composting, the BSF bioconversion process results in 70% less CO₂ emissions. Similarly, Komakech et al. (2015) who compared, from an environmental point of view, different organic waste treatment options in the context of Sub-Saharan African cities, showed that composting perform poorly in terms of global warming potential compared to other valorisation methods, including BSF treatment, due to direct emissions during the composting process. Overall, the choice of the best scenario should take into account the local context, and especially which aspect to prioritize, i.e. whether it is to treat large volumes of faecal sludge, produce affordable and sustainable animal feed products, or produce organic fertilizer, etc.

Chapter 5: Conclusion and outlook

Reviewing the literature and documenting case studies of implementation of BSF waste treatment method revealed that BSF technology is a promising solution to improving the recycling of organic waste, which is ineffective in most parts of the world. The BSF is indeed a beneficial insect in many respects. BSF larvae efficiently consume a wide range of organic materials, including food waste, animal manure, agro-industrial waste, and human waste. Doing so, they rapidly grow into an energy-rich biomass which is suitable for feeding monogastric animals, such as fish, poultry, and pigs. Therefore, in addition to improving organic waste management, BSF technology has the potential to make the animal production industry more sustainable by producing animal feed ingredients that can substitute conventional feed products, such as fishmeal and soybean meal, whose production and distribution are associated with high environmental and social impacts. Moreover, the revenues derived from the sales of the bioconversion products can incentivize organic waste management and provide economic opportunities for a wide range of actors, including farmers and small entrepreneurs in low- and middle-income countries. However, as BSF technology constitutes a relatively recent research topic, a number of technical issues still need to be addressed. In addition, limited data are available concerning the economic, environmental, and social performance of this valorisation option.

BSF technology is particularly promising in Ghana where improving organic waste recycling, producing affordable farming inputs such as animal feeds and fertilizer, and providing livelihood opportunities constitute priorities. As food waste (FW) and faecal sludge (FS) are high-impacting, nutrient-rich, and abundant waste streams in Ghana, the feasibility of valorising them using the BSF was explored in this study. From a technical point of view, a 10-week field work demonstrated that artificially rearing BSF and co-digesting FW and FS with BSF larvae using a low-tech system was technically feasible in Ghana. However, technical performance was evaluated based on a limited number of parameters and replications. Therefore, further research is needed, especially to characterize the bioconversion products (nutritional properties of the larval biomass, nutrient content of the waste residue, etc.), establish the optimal FS/FW ratio, and optimize rearing performance.

As for the economic aspect, the comparison of different scenarios through a cost-benefit analysis revealed that, in the Ghanaian context, the scenario in which FW and FS sludge are co-digested by BSF into both animal feed and fertilizer is the most likely to be profitable, followed by the composting scenario. By contrast, converting FW and FS into only animal feed is financially riskier as the probability of viability is much lower, compared to the two other scenarios. However, this economic viability study was constrained by the limited availability of quantitative data and was based on a number of simplifying assumptions and generalization of experimental results and case studies. In addition, comparing the economic performance of different valorisation scenarios requires taking into account additional aspects, such as the local market demand and social acceptance for the different valorisation products, the faecal sludge treatment capacity of each scenario, the environmental and social benefits associated with the different valorisation products, as well as the potential adverse environmental impacts associated with the various processes (e.g. direct emissions).

The study focused on the Ghanaian context. However, the low-tech system established as part of the technical feasibility study could be adapted to other low- and middle-income countries with tropical climates. Furthermore, this study provides a systematic method to evaluate the technical and economic feasibility of implementing a BSF bioconversion system. From a broader perspective, this study revealed, using the example of the BSF, that insects, as natural converters of organic matter, constitute great resources whose potential should be further explored for not only waste management, but also for agriculture, medicine, and the biotechnology industry.

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Appendices

Appendix A – Base values used for building financial models for the three scenarios

- Waste input and pre-processing
 - Composting scenario

Table 5.1 - Base values pertaining to waste input used for the composting scenario

Parameter	Value	Unit	Source
Waste input	1	tonne/day (wet)	Assumed value
FW ratio	75	% (wet weight)	<i>Fortifier™</i> plant's case study
Dewatered FS ratio	25	% (wet weight)	<i>Fortifier™</i> plant's case study
Conversion rate raw FS (RFS) to dewatered FS (DFS)	19	kg DFS/m ³ RFS	<i>Fortifier™</i> plant's case study
RFS input	13	m ³ /day	Value calculated based on the conversion rate of RFS to DFS

- BSF and BSF + composting scenarios

Table 5.2 - Base values pertaining to waste input used for the BSF and BSF + composting scenarios

Parameter	Value	Unit	Source
Waste input	1	tonne/day (wet)	Assumed value
FW ratio	75	% (wet weight)	Experimental value
Slightly dewatered FS ratio	25	% (wet weight)	Experimental value
FS density	1,001	kg/m ³	Radford and Sugden (2014)
Moisture content raw FS	95	% (wet weight)	<i>Fortifier™</i> plant's case study
FS drying time	3	days	Experimental value
Moisture content of FS after drying	70	% (wet weight)	Experimental value
Weight of raw FS to be dried to obtain a functional unit of FS	1.5	tonne	Value calculated based on moisture content of FS before and after drying
Daily FS input	1.5	m ³ /day	Value calculated based on FS density

- Waste treatment (BSF and BSF + composting scenarios)

Table 5.3 - Base values pertaining to waste treatment used for the BSF and BSF + composting scenarios

Parameter	Value	Unit	Source
Feeding rate	0.1	g/larva/day (wet)	Experimental value
Larval density	4 ⁶	larvae/cm ²	Value recommended by Dortmans et al. (2017)
Retention time in the waste treatment unit	12	days	Experimental value
Number of juvenile larvae to be used in the waste treatment unit	833.333	juvenile larvae/day	Value calculated based on the feeding rate and retention time

⁶ For the larval density, a value greater than that used in the waste treatment trials was assumed since the experimental value, which had been selected based on the availability of juvenile larvae during the field work, was too low in the context of a commercial facility. However, it was assumed that biomass production, and waste reduction performance were not affected by a change in the larval density. In reality, a greater larval density is expected to result in a lower biomass production and greater waste reduction.

- Products
 - Composting scenario

Table 5.4 - Base values pertaining to products used for the composting scenario

Parameter	Value	Unit	Source
Compost yield	0.54	kg of compost/kg of waste	<i>Fortifier™</i> plant's case study
Compost production	536	kg of compost/day	Value calculated based on compost yield

- BSF and BSF + composting scenarios

Table 5.5 - Base values pertaining to products used for the BSF and BSF + composting scenarios

Parameter	Value	Unit	Source
BSF larvae (BSF and BSF + composting scenarios)			
Moisture content BSF larvae	63	% (wet weight)	Experimental value
BSF larvae yield (wet)	0.12	kg of BSF/kg of waste (wet)	Experimental value
BSF larvae production (wet)	120	kg of BSF/day (wet)	Value calculated based on wet yield
BSF larvae production (dry)	45	kg of BSF/day (dry)	Value calculated based on wet production and moisture content of the larvae
BSF fertilizer (BSF + compost scenario only)			
Waste residue (WR) yield	0.40	kg WR/kg of waste (wet)	Experimental value
Waste residue production	405	kg WR/day (wet)	Experimental value
BSF fertilizer yield	0.54	kg compost/kg WR	<i>Fortifier™</i> plant's case study
BSF fertilizer production	217	kg compost/day	Value calculated based on fertilizer yield

- BSF rearing unit (BSF and BSF + composting scenario)

Table 5.6 - Base values pertaining to BSF rearing used for the BSF and BSF + composting scenarios

Parameter	Value	Unit	Source
Mating cages			
Oviposition rate	293	eggs/fly	Average of values reported in the literature (see Table 3.6) ⁷
Egg production	1,413,676	eggs/day	Value calculated based on larval production and hatching rate
Fly production	4,824	flies/day	Value calculated based on egg production and oviposition rate
Fly density	5,000	flies/m ³	Experimental value
Fly retention time	5	days	Experimental value
Number of oviposition media	5	media/cage	Experimental value
Media retention time	1	day	Experimental value
Hatchery			
Average weight of an egg	0.028	mg/egg	Booth and Sheppard (1984)
Hatching rate	60	%	Experimental value
Egg retention time	4	days	Experimental value
Egg density	200	eggs/cm ²	Experimental value
Neonate larvae retention time	5	days	Experimental value
Feeding rate neonate larvae	0.001	g/larva/day	Experimental value
Larvae nursery			
Production of juvenile larvae	841,751	juvenile larvae/day	Value calculated based on number of larvae needed for WT and nursery
Fraction of juvenile larvae kept in the rearing unit	1	%	Value chosen based on the case studies
Number of juvenile larvae kept in the rearing unit	8,418	juvenile larvae/day	Value calculated based on % of juvenile larvae kept in the rearing unit
Larvae retention time in the nursery	21	days	Experimental value
Feeding rate of larvae in the nursery	0.1	g/larva/day	Diener et al. (2009b)
Moisture content larval feed	70	%	Experimental value
Larvae density in the nursery	4	larvae/cm ²	Experimental value
Transformation rate of larvae into prepupae	80	%	Experimental value
Pupation chamber			
Prepupal production	6,734	prepupae/day	Value calculated based on transformation rate of larvae
Pupae retention time	13	days	Experimental value
Adult emergence rate	77	%	Experimental value
Pupae density	3	pupae/cm ²	Experimental value
Pupation substrate quantity	0.15	g/pupa	Experimental value

- Economic base values (all three scenarios)

Table 5.7 - Economic base values used for all three scenarios

Parameter	Value	Unit
Conversion US\$ to GHC	4.53	GHC/US\$

⁷ For egg production, the average of values reported in other studies was considered instead of the experimental value, as this latter value was abnormally low.

Appendix B – Calculation of the costs associated with the three scenarios

Costs considered in the analysis can be broken down in three categories, namely (1) investment costs, (2) production costs, and (3) other running costs

- Investment costs

Investment costs considered in the analysis included building and construction costs, equipment and machinery costs, and legal and registration costs.

- Building and construction costs

To estimate building and construction costs associated with each scenario, the main steps consisted in (1) estimating mean building and infrastructure (water, electricity, etc.) costs per unit area, and then (2) calculating the area required to treat 1 tonne of waste per day. Regarding building and infrastructure costs per unit area, the same values were considered for the three scenarios, i.e. ~544 GHS/m² for building costs and ~61 GHS/m² for infrastructure costs. These values were extrapolated from the case study of the *Fortifier*TM plant, since it was built using construction materials and techniques that are standard in the Ghanaian context and suitable for both a composting and BSF waste treatment facility. For the BSF scenario, area requirement was estimated by first calculating the area of the waste treatment unit based on the waste load. Base values used for the calculation are presented in Table 5.8. It was assumed that the waste treatment unit consisted of individual trays that could be handled manually by operators and stacked vertically to minimize space requirement.

Table 5.8 - Base values used for area requirement calculation in the BSF scenario

Parameter	Value	Unit	Source
Waste load	4	kg waste/m ² /day	Value calculated based on feeding rate and larval density
Stacking level	5	levels	Assumed value
Buffer space⁸	50	%	Assumed value

Once the area of the waste treatment unit estimated, the total facility's area was calculated by allocating a percentage of the total area to each unit, based on FORWARD and Ento-Prise's case studies (see Table 2.13) and data provided by Diener et al. (2009a). The additional area required for faecal sludge drying was extrapolated from the case study of the *Fortifier*TM plant. Land allocation values used for the calculation are presented in Table 5.9.

Table 5.9 - Land allocation values adopted for the BSF scenario

Unit	Land allocation in BSF scenario (%)	Area (m ²)
Waste and products processing		
Drying beds	-	16
Food waste handling	10	20
Waste treatment	50	100
Product harvesting	5	10
Boiling and drying of BSF larvae	5	10
BSF larvae storage	5	10
Rearing unit		
Mating cages	3	6
Hatchery	2	4
Larvae nursery	4	8
Pupation chamber	2	4
Lab (counting and weighing)	4	8
Other		
Employee facilities	5	10
Office	5	10
Total	100	216

⁸ Buffer space refers to the empty space requires for the operators to move around the racks in order to handle the treatment trays.

For the BSF + composting scenario, the same area values as for the BSF scenario were considered for units common to both scenarios. In addition, it was assumed that additional area was required for waste residue maturation, sieving and bagging of BSF compost, and compost storage. Space requirement for waste residue maturation was assumed to be 200m²/tonne of waste residue/day, based on data provided by Lohri et al. (2017), and space required for sieving and bagging of BSF compost, and compost storage was assumed to be the same as those required for respectively boiling and drying BSF larvae, and BSF larvae storage. Additional areas required in the BSF + composting scenario, compared to the BSF scenario are presented in Table 5.10.

Table 5.10 - Additional area required in the BSF + composting scenario

Unit	Area (m ²)
Residue maturation	70
Sieving and bagging of BSF compost	10
Compost storage	10
Total additional area	90
Total area in BSF +composting scenario	306

For the composting scenario, area requirement for faecal sludge drying was calculated based on the case study of the *Fortifier*TM plant, while that for composting was calculated based on the value provided by Lohri et al. (2017) (200m²/tonne of waste/day). Areas for food waste handling, employee facilities, and office were assumed to be the same as those in the BSF and BSF + composting scenarios. Finally, the area required for sieving and bagging, and compost storage was assumed to be three times that in the BSF + composting scenario as compost production is approximately 3 times higher in the former scenario compared to the later. Area values estimated for the composting scenario are presented in Table 5.11.

Table 5.11 - Area requirement in the composting scenario

Unit	Area (m ²)
Faecal sludge drying	469
Food waste handling	10
Composting and maturation platforms	200
Sieving and bagging	30
Storage	30
Employee facilities	10
Office	10
Total	759

○ Equipment and machinery costs

For the BSF and BSF + composting scenarios, a list of equipment needed was made based on the experimental system established as part of the technical feasibility study, as well as FORWARD and Ento-Prise's case studies. To assess the total quantity of each item, a number of base parameters pertaining to waste treatment, BSF rearing, and bioconversion products were quantified using experimental values or values recommended in the literature. Then, the total quantity of each item was expressed in terms of the defined base parameters, thus allowing their quantification. Unit prices were estimated through a market price study consisting of recording the price charged for the items of interest in several common shopping places in Accra (i.e. Madina Market and Accra Mall). For the composting scenario, a similar method was used for equipment and machinery costs estimation as data from the *Fortifier*TM plant's case study could not be used since the mechanization level of the facility was much higher than that assumed in this study. Table 5.12 and Table 5.13 present the list of equipment and associated costs for respectively the BSF scenario, and the composting scenario (the equipment list for the BSF + composting scenario is similar to that for the BSF scenario).

Table 5.12 - Equipment list and costs for the BSF scenario

Item	Quantity/unit	Unit	Total quantity	Unit price (GHC)	Cost (GHC)	Cost (US\$)
Bucket	40	kg of waste/bucket	25	5	125	28
Shovel	1	Shovel/operator	2	18	36	8
Bulk scale	1000	kg of waste/balance/day	1	181	181	40
Treatment container	12	kg of waste/container/retention time	1,042	75	78,125	17,246
Rack	15	containers/rack	70	500	35,000	7,726
Bowl (ant trap)	4	bowls/rack	280	0.6	168	37
Sieve	405	kg of waste residue/sieve/day (wet)	1	200	200	44
Harvesting container	20	kg of mature larvae/container (wet)	7	75	525	116
Gas stove	120	kg of mature larvae/stove/day (wet)	1	90	90	20
Cooking pot	120	kg of mature larvae/pot/day (wet)	1	20	20	4
Strainer spoon	1	strainer spoon/worker	2	20.5	41	9
Drying table	120	kg of mature larvae/table	1	200	200	44
Mating cage	7,500	flies/cage	4	136	544	120
Attractant container	1	container/cage	4	7	28	6
Water container	1	container/cage	4	7	28	6
Water spray	1	water spray/cage	4	15	60	13
Bowl (ant trap)	4	bowls/cage	16	0.6	10	2
Hatching container	480,000	eggs/container	27	75	2025	447
Mesh (m ²)	0.48	m ² of mesh/container	13	5	65	14
Rack	15	containers/rack	2	500	1000	221
Bowl (ant trap)	4	bowls/rack	8	0.6	4.8	1
Sieve	1	sieve/operator	2	50	100	22
Nursery container	7,700	larvae/nursery container	23	75	1725	381
Transfer container	1	container/nursery container	23	75	1725	381
Rack	15	nursery containers/rack	2	500	1000	221
Bowl (ant trap)	4	bowls/rack	8	0.6	4.8	1
Pupation container	1,800	pupae/container	49	15	735	162
Mesh	0.06	m ² of mesh/pupation box	3	7	21	5
Rack	30	pupation boxes/rack	2	500	1000	221
Bowl (ant trap)	4	bowls/rack	8	0.6	4.8	1
Desk	841,751	juvenile larvae/balance/day	1	300	300	66
Precision scale	841,751	juvenile larvae/balance/day	1	2,300	2300	508
Lab coat	1	lab coat/operator	2	25	50	11
Protection mask	1	protection mask/operator	2	15	30	7
Calculator	0.5	calculator/operator	1	17.99	18	4
Tweezer	2	tweezers/operator	4	36.24	145	32
Spoon	2	spoons/operator	4	0.5	2	0
Scoop	2	scoop/material	4	0.5	2	0
Bowl	9,600	juvenile /bowl/day	87	0.6	52.2	12
Plate	2	plates/operator	4	0.6	2.4	1
Water jug	2	jug/operator	4	3	12	3
Desk	0.3	desk/operator	1	300	300	66
Chair	0.3	chair/operator	1	250	250	19
Computer	0.3	computer/operator	1	1,300	1300	11
Rack	0.3	rack/operator	1	500	500	1
Dustpan and brush	0.5	dustpan/operator	1	4.5	4.5	1
Towel	2	towels/operator	4	3.95	15.8	3
Total					130,075	28,714

Table 5.13 - Equipment list and costs for the composting scenario

Item	Quantity /unit	Unit	Total quantity	Unit price (GHS)	Cost (GHS)	Cost (USD)
Bucket	40	kg of waste/bucket	25	5	125	28
Shovel	1	shovel/operator	3	18	54	12
Bulk balance	1000	kg of waste/balance	1	181	181	40
Thermometer	1000	kg of waste/thermometer	1	453	453	100
Sieve	536	kg compost/sieve/day	1	200	200	44
Desk	1	desk/office	1	300	300	66
Chair	1	chair/office	1	250	250	55
Computer	1	computer/office	1	1300	1300	287
Rack	1	rack/office	1	500	500	110
Total					3,363	742

- Other investment costs

Legal and registrations costs were considered. They include costs pertaining to registration of the company and product(s), and the acquisition of an EPA permit. They were calculated based on data from *Fortifier™* plant and Ento-Prise's case studies. Land acquisition was not included in the investments costs as it was assumed that a composting and/or BSF facility could benefit from a land provided by the municipality in which it operates.

- Production and other costs

- Labour costs

For the composting scenario, the number of operators needed to treat 1 tonne of waste per day was extrapolated from *Fortifier™* plant's case study, while for the BSF scenario labour requirement was estimated based on the case studies documented in Chapter 2: (section 2.2.4) and data provided by Diener et al. (2009a). In the BSF + composting scenario, labour requirement was calculated separately for the BSF and composting units based on the values used respectively in the BSF and composting scenarios. In addition, in all the scenarios, it was assumed that a plant manager was employed on a part-time basis (4 hours/week) to supervise the operation of the facility. Salaries' quantification was based on data provided by Jekora Venture Ltd. Base values used for the calculation of labour costs are presented in Table 5.14.

Table 5.14 - Base values used for the calculation of the labour costs

Parameter	Value	Unit	Source
Labour requirement for composting	3	operators/tonne of waste/day	<i>Fortifier™</i> plant's case study
Labour requirement for a BSF unit	2	operators/tonne of waste/day	Case studies and Diener et al. (2009a)
Operators' wage	700	GHS/month/operator	<i>Fortifier™</i> plant's case study
Additional employee	1	plant manager	Assumed value
Time allocation to the plant	4	hours/week	Assumed value
Plant manager's wage	250	GHS/month	<i>Fortifier™</i> plant's case study

- Consumable costs

For the composting scenario, consumable costs were estimated using data from the *Fortifier™* plant's case study. Like equipment and machinery costs, consumable costs associated with BSF and BSF + composting scenarios were calculated by expressing quantity for the different consumables in terms of the process base parameters, and quantifying unit prices through a market price study. Table 5.15 shows the list of consumables with associated quantities and costs for the BSF + composting scenario, which is a synthesis of the two other scenarios.

Table 5.15 - List of consumables with quantities and costs for the BSF + composting scenario

Item	Quantity /unit	Unit	Total quantity/ year	Unit	Unit price (GHC/unit)	Cost (GHS/year)	Cost (USD/year)
Cardboard	0.06	m2/eggie	438	m2	0.5	219	48
Wheat bran	6	kg/day	2,304	kg	0.72	1,659	366
Coco peat	0.39	kg/day	142	kg	3.5	497	110
Gas	1	kg/week	52	kg	10	520	115
Protection gloves	2	pairs of gloves/operator /day	2190	pairs of gloves	0.4	876	193
Marker pen	1	marker/month	12	markers	14	168	37
Dishwashing detergent	0.75	L/week	39	L	9.32	363	80
Sponge	2	sponges/week	104	sponges	0.825	86	19
Polypropylene bags for larvae	50	kg of larvae/bag	330	bags	2	660	146
Polypropylene bags for compost	50	kg of compost/bag	1583	bags	1	1583	349
Total						4,388	969

- Water and electricity costs

In all three scenarios, energy consumption was calculated by estimating the wattage of each appliance and the number of hours it was used per day. In the composting scenario, water consumption calculation was based on water consumption data provided by Cadena et al. (2009). For the BSF scenario, data from FORWARD case study, provided B. Dortmans (Mr. B. Dortmans, personal communication, 1st November 2017), were used to estimate water consumption. In the BSF + composting scenario, water consumption was calculated separately for the BSF and composting units using previous data. Then, electricity and water tariffs published by Electricity Company of Ghana Ltd (2017) and Ghana Water Company Limited (2015) were used to calculate water and electricity costs.

- Other costs

Other costs considered include operation and maintenance costs, product certification, depreciation costs, and income tax. Operation and maintenance costs were assumed to amount to 5% of the equipment and machinery's value and 0.05% of building costs. Compost certification must be renewed every two years at a fee of GHS 1,900. As no information was found regarding animal feed certification in Ghana, it was assumed that renewal rate and cost was the same as for compost. To calculate depreciation costs associated with buildings and equipment, the straight-line depreciation model was used. The base values used for the calculation are presented in Table 5.16.

Table 5.16 - Base values used for the calculation of depreciation costs

Asset	Useful life (years)	Salvage value (% of the initial value)
Building	20	60
Equipment	10	40

Finally, for the income tax that companies must pay on their annual profit, the tax rate is 25% (Ghana Revenue Authority, 2018).

- Revenues

Two sources of revenue were considered, namely the sales of the product(s), and tipping fees paid by private truck operators transporting the faecal sludge. Based on the data provided by JVL, it was assumed that tipping fees amounted to 1.5 GHS/m³ of faecal sludge in all three scenarios. In the composting and BSF + composting scenario, the selling price of the compost was set based on the price of *Fortifier™* compost, i.e. 0.5 GHS/kg. Table 5.17 compares this price to those of other organic and conventional fertilizers sold on the Ghanaian market. As shown in Table 5.17, the selling price of the *Fortifier™* compost is on average half the price of conventional fertilizer and in the same range of other organic fertilizers sold on the Ghanaian market.

Table 5.17 - Comparison of the selling price of different fertilizers on the Ghanaian market

Type of fertilizer	Selling price in Ghana (GHS/kg)	Selling price in Ghana (USD/kg)	Reference
NPK fertilizer	1.15	0.25	Ministry of Food and Agriculture (2017)
Urea	0.95	0.21	Ministry of Food and Agriculture (2017)
Fortifier compost (organic)	0.5	0.11	Data provided by IWMI and JVL
Other organic fertilizers (ACARP, YAYRA CLOVER)	0.3 – 1.3	0.07-0.28	Ministry of Food and Agriculture (2017)

In the BSF and BSF + composting scenarios, the price of dry BSF larvae was established based on the prices, on the Ghanaian market, of common feed products for poultry and fish (see Table 5.18).

Table 5.18 - Selling price of common feed products for poultry and fish on the Ghanaian market

Feed	Selling price in Ghana (GHS/kg)	Selling price in Ghana (USD/kg)	Reference
Local corn	2.25	0.50	USDA (2017)
Soybean meal	2.00	0.44	USDA (2017)
Broiler feed	2.10	0.46	USDA (2017)
Layer feed	1.80	0.40	USDA (2017)
Fishmeal (low grade)	4.08	0.90	Diener et al. (2014)
Fishmeal (high grade)	5.89	1.30	Diener et al. (2014)

It was assessed, as part of the EU-funded project PROteINSECT which investigated the use of insects as a novel protein source for animals, that the value of BSF meal is at least twice that of soybean meal but lower than that of fishmeal (FERA, 2016). Therefore, the price for dry BSF larvae was assumed to be 4.00 GHS per kg of dry larvae.

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